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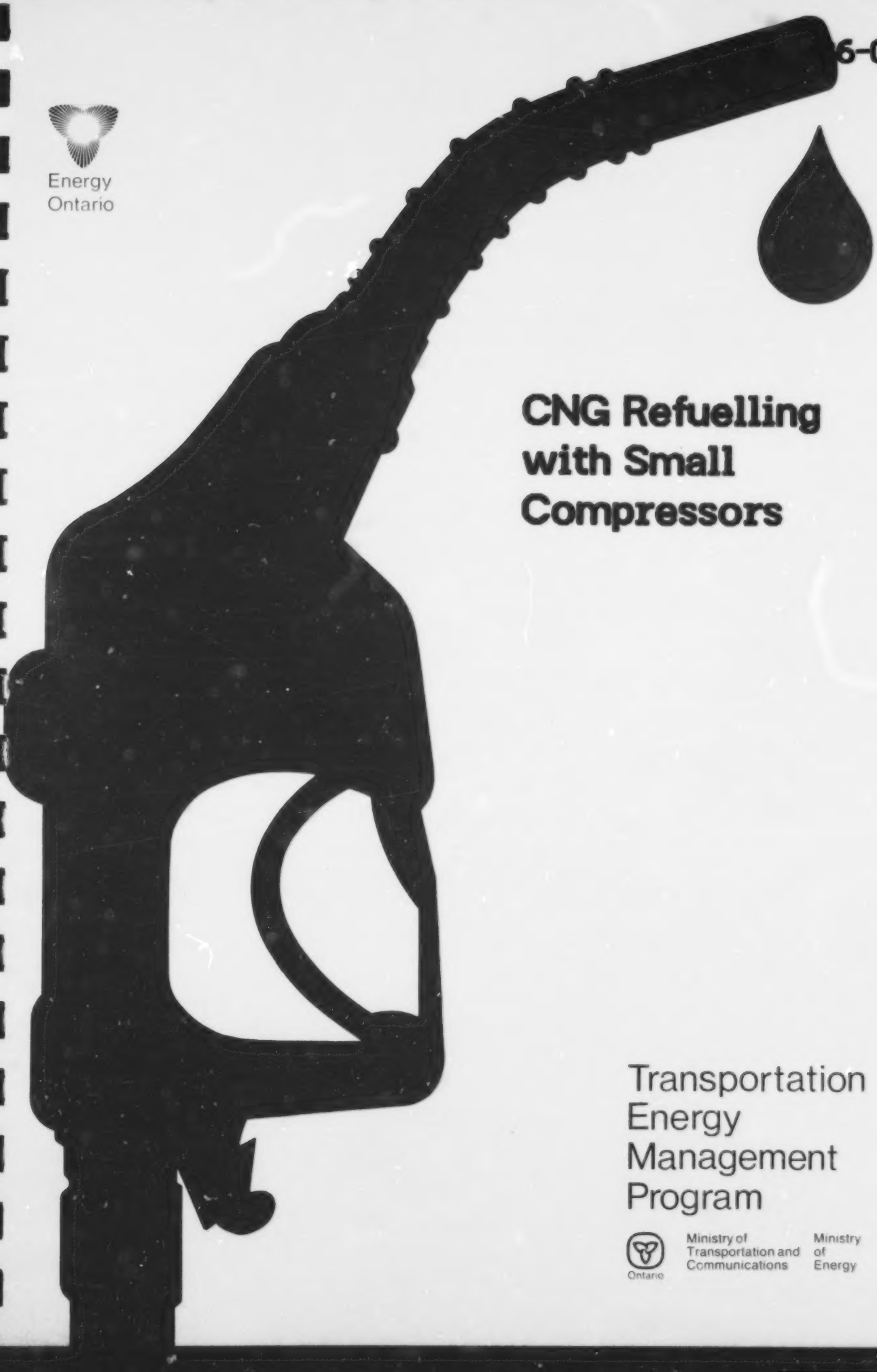

CNG Refuelling with Small Compressors

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CNG Refuelling with Small Compressors

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Abstract:
This paper reviews current small compressors designed for refuelling of CNG-powered vehicles. The compressors are intended for use by consumers or small fleet operators. The report examines design criteria, operating principles, performance, durability, and economic feasibility for application in home refuelling.

Key Words: compressors, CNG, performance, economic feasibility, fleet operation

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EXECUTIVE SUMMARY

The application of small compressors for refuelling natural gas vehicles is a relatively new concept. Currently, most vehicle refuelling is done at the fleet owners' compressor stations, and there are only a few public refuelling facilities in Ontario. To increase the penetration of natural gas into the transportation fuels market, there is a need to develop and establish refuelling facilities. The application of small compressors for home refuelling is one possible solution to accommodate the refuelling needs of natural gas vehicles.

The concept of home refuelling involves the use of small compressors to transfer natural gas from the residential gas system into vehicle storage cylinders. At present, three prototype small compressors are being marketed on a limited scale. They are manufactured by Rix Industries, Outboard Marine Corp. (OMC), and Bauer Industries, respectively. These compressors are designed to pressurize the natural gas in three stages, with interstage and/or afterstage coolers. The average compression ratio for each stage is relatively high, about 5:1, and the maximum output pressure is 22 MPa. Special piston rings made of silicon or nylon are used in this high pressure operation, and the compressor cylinders and pistons are lubricated with oil to prevent wear. Currently, most compressors are driven by a 1.5 to 3 kW electric motor, and the volumetric flow rate is 4 to 6 m^3/h, resulting in a typical refuelling time of 4 h for compact automobiles.

The small compressors have been marketed for a few years, but only a few units have been sold, mostly to gas utilities or gas research organizations for the purpose of compressor performance evaluation. Among the three prototype compressors, the performance of the Rix unit was most extensively investigated and documented by the Consumers' Gas Company (CGC) and the Canadian Gas Institute (CGI). However, in both studies the testing was limited to a maximum of 300 h.

In both the CGC and CGI studies, the major operational problem of the Rix unit was the large amount of lubricant/oil blow-by which escaped through the first-stage piston rings into the vehicles' regulators or storage cylinders. Other minor functional problems were also recorded, including faulty pressure relief valve, cracked cooling tubes, and fractured compressor pistons.

The energy requirement of the Rix unit was similar in both studies, with values of 45.9 kWh/100 m^3 and 52 kWh/100 m^3 from CGC and CGI, respectively. The compression efficiency of this make is estimated in this report to be approximately 60%.

For the other two compressors, the testing and documentation was very limited. The OMC unit was tested by Ford research for only two weeks and no test data are available. Similarly, there are no operating data on the Bauer unit.

Since most home compressor units will be operated by consumers with limited knowledge in the use of high pressure vessels, operational safety is one of the most important considerations. Most manufacturers claim their compressors are operationally safe and are equipped with a list of comprehensive safety features, such as emergency stop switches, pressure relief valves, and encapsulated electric motors. However, the duration of most compressor testing has been too short to establish a comprehensive data base for safety acceptance.

Noise is another important consideration for household application. With the Rix compressor, the whole compressor assembly is encapsulated and installed below grade to provide good sound insulation. According to the Consumers' Gas Company, the Rix compressor is very quiet in operation, and the noise level is acceptable to the users and neighbours. However, no actual noise level measurement was made.

In addition to performance, the economics of small compressor applications is an important factor to be considered by consumers. The economic feasibility of the home refuelling concept was analysed in this report by varying three system parameters: compressor cost, fuel cost, and vehicle kilometrage. Of these three parameters, compressor cost has the greatest impact on the economic attractiveness of the home refuelling concept. At the current typical compressor cost of $6600/unit, it is only marginally attractive for small fleet owners (two compressors, one cascade, and five vehicles each with 60 000 km/yr) because they could recover their total capital cost of $16,600/system in four years. At a compressor price of $3300/unit, the use of small compressors would have a pay-back period of 2.50 years and, therefore, be financially more attractive to fleet owners. For family applications, the use of small compressors will not be attractive until the compressor cost is reduced to $1500/unit.

Recent developments in improved natural gas storage facilities and technology have rekindled the interest in the home refuelling concept. Rix Industries is now marketing a second generation of small compressors, which promise performance superior to the earlier model; cost is also reduced to $3300/unit for volume purchase. In addition, the availability of adsorbent materials to store the natural gas at lower pressures would reduce the required compression stages, thereby reducing the compressor cost. All these latest developments would improve both the cost advantage and the performance of compressors -- the most important factors for the introduction of the home refuelling concept.

1/ INTRODUCTION

Natural gas can be used as an alternative to gasoline in motor vehicles. It has desirable combustion and emission characteristics [1,2,3], and at present, it is sold at a very competitive price. Throughout Canada, an increasing number of fleet vehicles are being converted to run on compressed natural gas [4]. The gas is stored on-board the vehicles in aluminum or steel cylinders at a pressure of 20.7 MPa (3000 psi).

Currently, most of the vehicle refuelling is done at fleet owners' compression stations, and there is only a limited number of refuelling stations available to the public. Even though the government of Canada is providing subsidies for building public refuelling facilities, so far there are only 18 compressor stations in operation in Ontario. To introduce natural gas vehicles in a large scale to the Canadian market, there is a need to develop and establish the refuelling facilities. One possible way of accommodating the refuelling needs of natural gas vehicles is to develop home refuelling systems which could take advantage of the well-established residential distribution system of natural gas.

The concept of home refuelling involves the use of a small compressor to transfer the natural gas from the home gas system into vehicle fuel storage cylinders. The vehicle could either be slow-filled by filling natural gas directly from the compressors or fast-filled from the cascades, a series of tanks that store compressed natural gas at a higher pressure than the vehicle storage tanks. The home refuelling compressor must be capable of pressurizing the natural gas from the home-line pressure of about 0.1 MPa to the desired storage pressure of 20.7 MPa. The rate at which the natural gas can be removed from the home gas supply system without disturbing the usage of the household appliances is restricted to about 4 m^3/h (2 scfm) [5]. This is equivalent to a pumping rate of about 4.2 L/h of gasoline. Thus, the refuelling time of a 10 L/100 km vehicle with a driving range of 160 km, is approximately 3.8 h.

Like all gases, the storage pressure of the natural gas at a particular temperature affects the storage density. In summer, the temperature inside a storage tank may be as high as 35°C, and at this temperature and 22 MPa storage pressure, the density of natural gas is 171.3 kg/m^3. In

winter, the average ambient temperature is -10°C, and the density of the natural gas is 180 kg/m^3 at 16.7 MPa storage pressure. This relationship is displayed in Figure 1, the basis of which is provided in Appendix A.

The slight difference in natural gas storage density between summer and winter storage temperatures will result in a seasonal difference in vehicle driving range. At the seasonal storage conditions described, a vehicle with fuel consumption of 10 L/100 km and a total natural gas storage volume of 130 L will have a maximum driving range of 356 km in summer and 377 km in winter. Consequently, most small compressed natural gas (CNG) compressors have an output pressure selector switch to provide adjustment for the desired seasonal storage pressures, and the maximum output pressure can be varied from 16 to 22 MPa.

The purpose of this report is to study the technical and economic feasibility of the home refuelling concept. At present, small compressors available for natural gas refuelling are at a prototype stage. Only a few gas utilities are experimenting with them to determine their suitability to their customers. Cost, durability, safety, service, quiet operation, and minimal maintenance are the primary considerations in deciding the most suitable compressor for this application. In this study, the basic designs of currently available compressors are reviewed, and the operating experience with these is discussed. In addition, the economic feasibility of the home refuelling concept is investigated by examining two possible applications:

1/ small fleet operation

2/ family-owned commuter vehicles

2/ COMMERCIAL AND PROTOTYPE HOME COMPRESSORS

2.1/ Background

In recent years, three makes of home compressor were introduced to the marketplace: the Rix, OMC, and Bauer compressors. These are designed to pressurize the natural gas in three stages, with interstage and/or after-stage coolers. Commonly, the average compression ratio for each stage is 5:1, and the compressed gas in each stage is cooled before subsequent compression.

Since the compressors operate at high pressures, they are commonly recommended for installation in open areas (i.e., outside of buildings) to minimize the dangers arising from gas leaks. In addition, the compressor piston rings are made of special silicon or nylon materials to endure the high pressure operation.

The following section will discuss the special features of the three available compressors. A summary of technical and cost information on these compressors is lsted in Tables 1 and 2.

2.2/ Rix Compressor

The Rix home compressor (HOMGAS Model HG-3) is a three-stage reciprocating unit with an axial piston drive. The compression ratios are 6:5, 4:1, and 5:6 for the first, second, and third stages, respectively. A 1.5 kW electric motor is directly coupled to the compressor via a jaw coupling and drives the compressor pistons at 1750 rpm. Since the compressor operates at relatively high compression ratios, the piston rings are teflon-reinforced with bronze wires, and the compressor valves are made of stainless steel.

The compressor, motor, and intercoolers are enclosed in a containment vessel. An oil pump suspended below the compressor and coupled to the main drive pumps cooling/lubricating oil from the bottom of the containment vessel to the external exchanger located at the top of the vessel. The cooling oil returning from the heat exchanger splashes over the motor, compressor, and bearings, thus providing cooling and lubrication.

Interstage cooling after each compression is provided by cooling coils submerged in the oil sump located at the base of the containment vessel.

The volumetric output capacity of the Rix compressor is 4.07 m^3/h. At this rate, it is capable of filling a 22 m^3 storage capacity in 5.45 h. The compressor unit has an output pressure limit switch which can reset the output pressure to either a "winter" setting of 16.7 MPa or a "summer" setting of 22 MPa. Figure 2 shows the major components of the Rix compressor system, and Table 3 is a list of its standard equipment.

2.3/ Outboard Marine Corporation (OMC) Compressor

The OMC compressor with slow-fill and quick-fill components is illustrated in Figure 3. The basic design of this compressor is similar to the Rix unit. The OMC compressor comprises three compression stages and is driven by a 2.24 kW electric motor. The working pressure is 0.62, 4.65, and 24.82 MPa for the first, second, and third stages, respectively, each having interstage air coolers in between. The volumetric flow rate is 5.1 m^3/h, and at this rate, a 22 m^3 storage capacity can be refilled in 4.45 h. Unlike the Rix compressor, the OMC unit has a factory-installed coalescing filter at the outlet to prevent excess lubricating oil from leaving the compressor and perhaps blocking the pressure regulator or storage system components on the vehicle. In addition, a ball-type check valve is installed at the discharge probe to eliminate backflow of compressed natural gas and thereby provide for easy disconnection after refuelling.

2.4/ Bauer Compressor

The Bauer home compressor system is illustrated in Figure 4, and a list of its components is presented in Table 4. The unit consists of a three-stage, air-cooled, V-belt-driven gas compressor designed specifically for high pressure natural gas applications. The compressor piston is driven by a 2.24 kW electric motor at 1200 rpm, the lowest speed of all three compressors described. This lower operating speed may reduce piston and cylinder wear, and a longer compressor service life may be expected. The volumetric output is 6.79 m^3/h at the maximum discharge pressure of 34.47 MPa.

2.5/ Operating Experience and Performance

The availability of these small home compressors for refuelling vehicles has generated a great deal of interest from several natural gas utility companies and research institutions. In Ontario, the Consumers' Gas Company (CGC) is pioneering the evaluation of these small home compressors. The company has purchased two compressor units (one from Rix, the other from OMC) in order to monitor their performance. In addition, the Canadian Gas Institute (CGI) has studied the performance of the Rix compressor, and Ford Research at Dearborn has investigated the performance of the OMC compressor for fast refuelling.

In the Consumers' Gas Company study, the Rix compressor was installed below grade in an employee's residence, and it was tested over a 288 h period. Initially, the compressor worked well, but after operating for 34.25 h, the piston and valve stem of the second stage were fractured due to the continuous impact between them. According to the Rix company, an installation error had resulted in incorrect clearance between the piston and valve, causing their impact. The problem was rectified by correctly installing a new piston and cylinder assembly.

Other minor problems not associated with the basic design of this compressor were also encountered. There was a faulty third-stage relief valve which opened at 16 MPa instead of 22 MPa. After the valve was replaced, the compressor operated properly again. Also, there were difficulties with disconnecting the refuelling probe from the vehicle immediately after the compressor shut down. On certain occasions, the high pressure gas had leaked back to the containment vessel through the third-stage cylinder. Consumers' Gas Company later installed a check valve in the refuelling probe to prevent the backflow of high pressure gas into the compressor.

The major operational problem of the Rix compressor was the backflow of the cooling/lubricating oil into the delivery line. The lubricant was blown past the piston rings and deposited in the vehicle fuel cylinder and regulator, causing the engine to idle roughly and stall frequently. An average oil blow-by rate of 24 mL/h was recorded by Consumer's Gas Company [6]. Consequently, periodic oil draining from the vehicle

regulator was required to ensure reliable engine operation. The above problems, their consequences, and the corrective actions taken are summarized in Table 5.

The performance of the Rix compressor was also studied by the Canadian Gas Institute, wno reported 12 operational failures within 208 h of operation [7]. According to the Institute's report, four of the failures were design related, six were of a mechanical nature, and the remaining two failures resulted from poor workmanship. A brief description of the compressor malfunctions is provided in Table 6.

In the CGI study, the mechanical failures of the Rix unit were attributed to a faulty pressure relief valve and overloading of the protection heaters [7]. The high pressure stage relief valve malfunctioned and occasionally opened, causing a leakage of natural gas into the containment vessel. As a result, the compressor drew gas from the vessel through the vent hole which is located internally on the first-stage suction line and produced a close cycle stalling condition. The original protection heater, #17$^{1}/_{2}$, rated for 11.5 to 12.3 A, burned out. After replacing it with a higher rating protection heater, it was found to be inadequate still. Finally, a new set of #B22 heaters rated at 13.7 to 14.6 A was installed, and the compressor was back in operation.

Poor quality of workmanship was considered to be the cause of two compressor shut-downs [7]. The operation of the compressor was stopped because of cracking of the intercooling tubes. This cracking was caused by human error during installation, i.e., incorrect or over-tightening of the connecting screw. In both cases, the natural gas leaked and pressurized the containment vessel. The problems were rectified by correctly replacing the cracked tubes.

The four design-related failures were deemed to involve the fracture of either the second- or third-stage high pressure discharge valves [7]. In all cases, low interstage pressure was reported. According to CGI, these failures were due to the metallurgical composition of the valves and the large amount of excess lubricating oil blow-by in the compressor cylinder. CGI reported the rate of oil carry-over as 51 mL/h, which is 2.1 times greater than the amount reported by Consumers' Gas. In all

instances, the fractured valve was replaced, but the replacement lasted only for a maximum of 60 h of operation. Finally, a splash guard was installed under the first-stage piston, thereby reducing the oil carry-over to 16 mL/h. After that, there were no further valve failures, and the test was completed after 250 h of operation.

An OMC unit was set up for quick-fill operation at a Consumers' Gas refuelling depot. To date, this unit has delivered 300 h of service without any major problems. However, details about its performance and operating history are not available, yet.

The OMC unit was also purchased by Ford Research for slow refuelling of their natural gas vehicles. The unit was only tested for two weeks, and no start-up problems were reported. However, the Ford Research staff showed concern about the exceptionally high rate of natural gas being drawn into the compressor. As a result, air was also drawn into the compressor cylinder, creating an extremely dangerous situation [8]. General Motors and Philiphedia Electric have also purchased OMC compressor units. Their initial response to the unit was good, but operating and performance data were not available [9].

The Bauer Company Inc. has not sold any compressor units in Canada, and only a few units have been purchased by gas utilities in the United States [10]. At this stage, they are unable to divulge detailed information on results with these units.

In summary, both the Consumers' Gas Company and the Canadian Gas Institute test results showed that the Rix compressor did not generate any insolvable maintenance or operating problems. The unit ran quietly without any complaints from users or neighbours. However, both studies reported problems with the following:

1/ excess oil blow-by clogging the vehicle regulator,
2/ cracked exhaust valves in the high pressure cylinders,
3/ faulty relief valves, and
4/ backflow of compressed natural gas due to cracked valves in the refuelling probe.

No performance data are available for the OMC and Bauer compressors as yet.

2.6/ Performance

Compression efficiency is a major criterion in evaluating the performance of compressors. The theoretical power requirement of compression can be estimated by using the following:

- entropy-enthalpy diagrams
- isentropic formulae

In this report, both methods of calculation are applied to the Rix compressor by using the design specifications (such as intercooler heat removal capacity, compression ratios, and volumetric flow rate) and the physico-chemical properties of natural gas. The theoretical power determinations of each compression stage by both methods are shown in Tables 7 and 8, and the details of the calculations are provided in Appendix B. The results show that the theoretical compressor power determined from the two methods is in agreement.

For the Rix compressor, the total power requirement determined by the enthalpy-entropy diagram is 0.882 kW, and the overall compression efficiency is 59%. The power requirement obtained by the isentropic formula shows a higher value of 0.9016 kW and an overall compression efficiency of 60%. The difference between the two results is rather small.

The actual energy requirement of the Rix compressor is 45.9 kWh/100 m^3 and 52 kWh/100 m^3, as reported by the Consumers' Gas Company and the Canadian Gas Institute, respectively. These values are much higher than for a 18.5 kW compressor, which is reported to be 16.0 kWh/100 m^3 [11]. The higher actual energy consumption confirms the prediction of the lower theoretical compression efficiency of the Rix unit.

2.7/ Safety and Environmental Issues

One of the most important aspects of a small home compressor is its inherent safety features, because these units will be operated by

consumers generally having little knowledge in the use of high pressure vessels. The natural gas is compressed to a high pressure (22 MPa), and major gas leaks may result from defective compressor valves or faulty gas line connections. Under these circumstances, explosions may occur if the gas is ignited. Consequently, most compressors are equipped with a number of comprehensive safety features to ensure safe operation.

The major safety feature of the Rix compressor is the enclosure of the compressor assembly, the electric motor, and all working parts in a containment vessel fabricated from standard 10 in. seamless pipe. Any leak from the gas flow system (including intercoolers, piston blow-by, or loose fittings) will be contained within the capsule and recirculated through the compressor. Prior to start-up of the compressor, the containment vessel is evacuated. The vessel is then filled with natural gas by opening the vent hole in the suction line to the first-stage cylinder, creating a non-combustible environment (100% natural gas). The electrical components are also explosion-proof, meeting Grade D specifications of the USA National Electrical Code. In case of excess pressure buildup in the capsule, a relief valve will vent the excess gas when the capsule pressure exceeds 1.72 MPa, which is only 25% of the capsule design limit.

Although the Rix unit has a lot of standard features, some additional measures are desirable. An emergency stop switch could be installed to turn off the compressor if gas leakage is detected. In addition, a more reliable check valve could be used in the outlet probe to prevent the backflow of compressed gas into the compressor.

The safety design of the OMC compressor is different from that of the Rix. Instead of encapsulating all the compression equipment, the OMC compressor and motor assemblies are covered in a cabinet. The main safety feature is the explosion-safe electric motor, which is enclosed in an airtight housing. The safety records of both Rix and OMC compressors are very good as no fires or explosions have been reported by the testing organizations.

Noise is another important consideration for consumer acceptance of a household appliance. At present, most home compressor manufacturers

accomplish noise reduction by enclosing the compressor assemblies in heavily insulated cabinets. According to Consumers' Gas, the Rix compressor was very quiet in operation, since the bulk of the compressor assembly was encapsulated and installed below grade. Only a muffled humming sound was audible, and the noise level was acceptable to the user and the neighbours. However, no actual noise level measurements were carried out.

3/ HOME COMPRESSOR ECONOMICS

3.1/ Assumptions of Economic Analysis

There are many parameters which must be considered when evaluating the economic feasibility of converting transportation vehicles to use natural gas as a fuel [12]. Some assumptions must be made about vehicle use and operation in the future and about future business and economic conditions. This economic feasibility analysis is directed toward the concept of home refuelling of natural gas vehicles by home owners and small fleet operators.

Table 9 lists the economic information which must be known before a precise feasibility analysis can be conducted. The driving force behind the use of natural gas as a transportation fuel is the fuel cost saving. This saving arises from displacing gasoline with the less expensive natural gas. Large fuel cost savings are essential for economic feasibility, and the largest savings are associated with situations currently characterized by high vehicle fuel consumption per kilometre travelled or many kilometres travelled per vehicle per year. The objective is to generate sufficient savings to realize an acceptable return on the capital invested over the lifetime of the equipment.

Refuelling facility costs depend on the type of refuelling system. Slow-fill systems are, as a rule, less expensive than quick-fill systems. Often, a combination of each is desired for a given fleet.

The tax status of the party owning the fleet has a large influence on the economic feasibility of conversion. For taxable organizations, depreciation of assets and interest paid on money borrowed for vehicle conversion and refuelling facilities can offset taxable income. An investment credit of $600 per vehicle is granted by the federal government, and the Ontario government provides sales tax exemption for new natural gas vehicles.

In this analysis, the conversion cost of each vehicle is assumed to be offset by the tax credits available. Family operations, however, could not take advantage of the equipment depreciation write-off and must gauge economic feasibility in savings realized by reduced operating costs.

The current price differential between gasoline and natural gas is likely to change in the future. Being able to program future price projections allows one to make educated decisions about economic feasibility.

For the subject case of vehicle conversion, the following assumptions can be applied:

- Past vehicle data (kilometres travelled and fuel used) are indicative of future vehicle data.
- The vehicles will be used for the same purposes as in the past.
- The conversion equipment and refuelling equipment will have a useful life of 10 years.
- Vehicle conversion equipment is transferable to replacement vehicles.
- There will be a 10-year depreciation of conversion and refuelling equipment.
- The costs are differential costs above those required for operation of gasoline-fuelled vehicles.
- The site space required for refuelling is already owned.

The 10-year life of equipment is based on current accounting practices and is not a reflection of the estimated real useful life of the equipment. A useful vehicle lifetime of five years is assumed for fleet operation, whereas the family vehicle is assumed to have a 10-year lifetime.

3.2/ Fleet Case Studies

To illustrate how the previously defined economic analysis equations can be used to determine the economic feasibility of converting vehicles to use natural gas as fuel and refuelling with small compressors, the following sample fleets are constructed:

Fleet #1 -- A two-vehicle family composed of a passenger car and a station wagon. The cost of the compressor is $6600 per unit.

Fleet #2 -- A five-vehicle delivery fleet consisting of medium-size vans and/or light trucks. The refuelling system requires two compressors ($6600/unit) and a cascade ($3400), for a total cost of $16,600.

Fleet #3 -- Same as Fleet #1, using future generation of home compressors (at a bulk purchase cost of $3300 per unit).

Fleet #4 -- Same as Fleet #2 but using bulk purchase cost of home compressors (i.e., $3300 per unit), bringing the total refuelling system cost to $10,000.

These fleets were chosen to represent a wide range of possible applications and to show how vehicle parameters, fleet operation, and compressor design and cost affect economic feasibility.

Fleet #1 could easily represent a family with members using two vehicles for their daily routine (e.g., shopping, to and from work, or holiday trip). Fleet #2 is representative of parcel delivery or bakery delivery van fleets. Fleets #3 and #4 are basically the same as Fleets #1 and #2, respectively, except that they are using the next generation of refuelling compressor at costs less than half of the current compressors. Before discussing assumptions specific to this fleet, however, some mention should be made of the general assumptions used for all the fleets.

Gasoline price, including all taxes, is assumed to be $0.47/L. The cost of natural gas is $0.23/L of gasoline equivalent. The natural gas price is based on the energy equivalent of 1 L of gas equal to 0.96 m^3 of natural gas. The cost of gasoline is assumed to increase at a rate of 3% per year above inflation, whereas natural gas is assumed to increase at a rate of 2% per year above inflation. There is no specific rationale for the price increase assumptions except that gasoline currently seems to be relatively inexpensive, whereas natural gas has just recently attained all-time high prices.

The vehicle fuel economy is assumed to be no better when using natural gas as compared to gasoline, because the actual fuel consumption penalty or advantage of using natural gas is not confirmed.

The vehicles in the fleet are assumed to use natural gas 100% of the time. While many users claim reductions in maintenance costs for vehicles converted to use natural gas, it is assumed conservatively here that no benefit would be obtained. The compressor energy requirements are

based on typical data reported by an actual user (Consumers' Gas Company), whereas the compressor maintenance cost is only an estimate. It is based on a compressor life of 5000 h before any major overhaul, which costs $700, and the total lubricant/oil cost is $100 for that life cycle. According to the above estimates, the compressor maintenance cost is $\$0.04/m^3$.

Both maintenance and electrical costs are assumed to remain constant in real dollars. The inflation rate is assumed to average 5% in the near future.

The interest rate on accrued saving is the rate applied to money saved which would have normally been spent on gasoline. While there are many uses for this money, which could return less or more than the 10% assumed here, this rate is chosen because it is the current short-term interest rate available. The interest rate on long-term debt is assumed to be 13.75%, typical for the current time period. It was assumed that the down payment on the investment would be 50% of the total investment.

Through the use of a computer program (as illustrated in Appendix C), the data for each of the four fleets are analysed. The program was designed to allow easy changes and speedy manipulation of the input value(s). The program is also very useful for determining the sensitivity of base fleet results to single variable changes such as compressor cost, vehicle kilometrage, or interest rates.

The economic analysis assumed the following:

- $600 tax grant provided by the federal government;
- the 7% rebate on provincial sales tax for new vehicles converted to use natural gas, assuming that the average cost of a new vehicle is $14 000 and the sales tax rebate is $980.

Based on the above assumptions, the total tax credit for a new vehicle converted to use natural gas is $1580 in Ontario.

The lifetimes of the conversion equipment and compressor are assumed to be 10 years, with an assigned salvage value of zero at that time. Straight-line depreciation is used over the assumed 10-year lifetime.

This is done for accounting and tax purposes. At the end of each year, the outstanding principal would be paid off in equal amounts over the 10-year lifetime. The interest expense is based on the outstanding principal amount each year. Thus, interest payments dwindle each year throughout the equipment's lifetime until these payments reach zero in the eleventh year.

The cash flow is calculated by adding the net saving to the annual depreciation. It is a measure of the actual cash that will accrue to the compressor owner for each year of operation.

The investment tax credit is subtracted from the cost of conversion and compressor to yield the actual cost.

For the families using home compressors, they have to pay tax for their interest from the accrued saving, whereas the corporation's taxable amount is the difference between the fuel saving and maintenance costs, operating cost, and interest on debt.

3.2.1/ Family Applications

The assumptions specific to Fleets #1 and #3 are as follows:

- two vehicles in the family;
- 18 000 km per year average vehicle use;
- 12 L/100 km average vehicle fuel consumption;
- slow-fill refuelling system, requiring no paving or grading of the refuelling site; and
- total debt of investment, 50%.

These assumptions are reflected by the input data shown in Table 10.

Tables 11 and 12 show the results of the economic analyses for Fleets #1 and #3, respectively. The sample calculations are shown in Appendix C. For Fleet #1, the analysis shows that the present value of the accumulated cash flow at the end of compressor life is $1108, which is much less than the original equipment cost of $6600. At the end of the equipment life, the high original equipment cost could not be recovered by the accumulated fuel savings. This shows that investment in a small

compressor is uneconomical for a family household with two cars. For Fleet #3, with a lower original compressor cost of $3300, the total accumulated fuel saving is $3961. The original investment will be recovered just after the eighth year of operation (discount pay-back period). Also, the return on asset is unattractive at 12%

Besides the capital cost of the compressor, the annual kilometres travelled of each vehicle is another important variable that affects the discount pay-back period. Figure 5 shows the change of discount pay-back period with the annual distance travelled by each vehicle in the family. To recover the $3300 per unit compressor cost, a family with vehicles travelling 20 000 km/year and 40 000 km/year would yield discount pay-back periods of 7.5 and 3.5 years, respectively.

The increase in vehicle-kilometres travelled improves the economic attractiveness of the home compressor application. However, it is unlikely that family vehicles would travel 40 000 km/year, and the 3.5 year pay-back period would not be achievable in family operation. The major obstacle for small compressor refuelling is high initial cost. For family applications the compressor cost must be reduced to $1500 per unit (to have an acceptable discounted pay-back period of three years).

3.2.2/ Small Fleet Applications

The following are the assumptions common to Fleets #2 and #4:

- five vehicles (delivery vans or light trucks);
- 30 000 km per year average vehicle use;
- 15 L/100 km average fuel economy;
- no paving or grading of the refuelling site necessary;
- two compressor units required, one for slow-fill and one for fast-fill; and
- the cost of the cascade, $3400.

These assumptions are reflected by the input data shown in Table 13.

Results of the economic analysis for Fleets #2 and #4 are shown in Tables 14 and 15. For Fleet #2, with an original investment of $16 600, the average annual cash flow is $2066, and the discounted pay-back period

is just over 7.5 years. For Fleet #4, the annual cash flow is only $1757, which is lower than the values for Fleet #2. The result is not surprising since the cash flow is the sum of the depreciated value of the capital investment and net savings. Therefore, even with an increase in fuel savings, the cash flow of Fleet #2 is reduced mainly because of the lower depreciated value of capital investment. Finally, the main advantage of the lower original capital investment of Fleet #4 is the shortening of the pay-back period to five years.

The influence of the annual distance travelled of the fleet vehicle on the discounted pay-back period is shown in Figure 6. If the distance travelled by Fleet #2 vehicles was increased from 30 000 to 60 000 km/year, the discounted pay-back period would be reduced from 7.5 to 4 years. For Fleet #4, with a lower compressor cost of $3300 per unit, the discounted pay-back period would be reduced from 5 to 2.50 years for the same increase in annual distance travelled by the fleet vehicles. This shows that the application of small compressors would be economically attractive to small fleet owners with high vehicle-kilometrage (70 000 km/year) at a compressor cost of $3300 per unit.

In summary, the above economic analysis illustrates that the small compressors application is economically more attractive to small fleet owners than to family users. The small fleet operation usually consists of four or five vehicles, each with a higher annual kilometrage and higher fuel consumption, factors which contribute to the increase of the fuel savings. Consequently, the fuel cost saving of the fleet operation is increased and the rate of return is improved as compared to family uses.

4/ MARKETABILITY

The marketability of the home refuelling concept depends on two major factors: the performance and the cost of small compressors. There are several small compressor manufacturers (OMC, Rix, Bauer), but performance data are available only for the Rix compressor.

The Consumers' Gas Company and the Canadian Gas Institute have each tested the Rix unit, and their results show that the compressor does not have any major maintenance or operational problems. The unit runs quietly without any complaints from users or neighbours.

The only major design problem was the excess lubricant/oil blow-by. Currently, Rix is marketing a second-generation home compressor (Figure 7) in which a splash guard is added to the first-stage piston to minimize the loss of lubricating oil. This helps to prevent the oil from entering the first stage, thereby reducing the amount of oil blow-by. Extra safety features, such as an emergency shut-off switch, have also been added to this unit. Although Rix Industries has claimed an improvement in the performance of its new compressor, the unit must be further investigated to establish its durability, maintenance, and performance. Aside from the Rix compressor, the performance of the other compressor models is not well established or documented. These compressors must also be tested to attain a better understanding of their performance.

In addition to compressor performance, capital cost is an important factor for consumer acceptance. Currently, the cost of a small compressor is roughly in the range of $5000 to $7000 per unit. The energy consumption of the Rix compressor is 2.53¢/m^3, and the maintenance cost is estimated at $0.04/$m^3$. With the addition of the above costs, the total cost of refuelling with natural gas is 27.6¢/m^3 or 26.5¢/L gasoline equivalent. Consequently, the fuel cost saving of using natural gas instead of gasoline would be 20.5¢/L, based on a gasoline cost of 47¢/L. As indicated in the economic analysis, the fuel saving of running two family-owned natural gas vehicles could not economically justify the purchase of the small compressor. The cost/benefit relationship indicated that the family would require more than 10 years to recover their capital

investment of $6600. Thus, the high capital cost of the compressor dampens the marketability of the home refuelling concept.

Recent compressor development has indicated that the cost of the next generation compressors will be reduced. According to Rix Industries, the cost of the new Rix compressor is $3300 per unit with a minimum order of 1000 units. Based on this future cost, the concept of home refuelling is economically attractive for small fleet owners. For example, running a few taxis or delivery vans travelling an average of 60 000 km/year, the operators could recover their capital in 2.50 years.

The expected reduction of compressor cost is also expressed by ICG Industries, who will market a new compressor in the fall of 1984. According to ICG, the cost of each unit would be around $2000, but the technical information is not yet available.

In addition, recent development of adsorbent materials that permit the natural gas to be stored at a lower pressure may improve the economics of home refuelling. Carbons such as Amoco-GX-32 or Saran (Darcy type) showed maximum gas storage density at 11 MPa. At this lower operating pressure, the compression work is reduced and the cost of the compressor may be significantly reduced. Thus, the application of these carbon adsorbants may improve the economic feasibility of the home refuelling concept.

In summary, the recent developments in refuelling technology, such as the second-generation Rix unit and the low storage pressure adsorbent materials, plus the reduction of compressor costs, have revived enthusiasm for the use of small compressors. However, further research work is still required to prove the small compressor is technologically and economically feasible for home refuelling by fleet owners or family users.

5/ CONCLUSIONS

The objective of this study was to investigate the current technology and economics of small compressors. The design criteria, operating principles, performance, and durability of commercially available small compressor units were reviewed. In addition, the economic feasibility of the home refuelling concept was studied for its applications by family users and small fleet operators. The results of this study were as follows:

1/ Three major compressor manufacturers, Rix Industries, Outboard Marine Corporation (OMC), and Bauer Industries, have introduced prototype small compressors specifically designed to meet the needs of home refuelling of CNG vehicles. These compressors provide an average gas flow rate of approximately 4 m^3/h and can produce the required tank pressure, viz, 20.7 MPa (3000 psi). At these flow rates the typical refuelling time for a compact automobile with empty tanks is approximately 4 h.

2/ The Rix compressor was tested comprehensively by the Consumers' Gas Company (CSG) and the Canadian Gas Institute (CGI). The compressor had operational problems, such as a faulty pressure relief valve, cracked cooling tubes, excess lubricant/oil blow-by, and fracture of the compressor piston. However, as a prototype, the compressor unit was considered to be acceptable.

3/ The average compression energy consumption of the Rix unit was found to be 49.3 kWh/100 m^3. The overall compression efficiency is estimated to be 60% in this report.

4/ The high cost of compressors is a major obstacle to their introduction into the consumer market. As indicated in the economic analysis, even at a volume price of $3300 per unit, the use of small compressors is not economically attractive to home users (two vehicles/family and each vehicle travelling 20 000 km/year). Furthermore, $3300 is a special volume price not available to the average consumer. To yield an acceptable discounted pay-back period of three years for family users, compressor cost must be reduced to $1500 per unit.

5/ At the current retail price of $6600 per unit, the use of small compressors is only marginally attractive to small fleet owners (five vehicles/fleet and 60 000 km/vehicle/year) with a pay-back period of four years. At a volume price of $3300 per unit, the use of small compressors would be economically more attractive to small fleet owners with a pay-back period of 2.50 years.

In summary, this study has revealed that although a number of home compressors have been offered by US suppliers for CNG applications, these are still prototype units. Their present prices make then uneconomical to either home users or small fleet operators. However, future mass production may reduce their prices to as low as one-quarter of the present level, at which point they would become cost-effective for both business and home applications. Thus, technical evaluation of the concept and existing hardware is justified. To-date, only a limited amount of evaluation has taken place, and the long-term durability, maintenance, and safety characteristics of existing hardware remain to be assessed. In addition, improved hardware is being introduced, which requires continuous unbiased evaluation.

6/ RECOMMENDATIONS

This study reveals that the testing of the existing small compressors has been very limited. Previous compressor studies have failed to collect certain important information, such as long-term durability, maintenance costs, safety, and environmental effects. These data are important for consumers in deciding whether to purchase a small compressor. To explore the viability of the home refuelling concept, the following areas should be investigated:

1/ The economic and maintenance data for the use of small compressors by small fleet operators should be gathered to illustrate the potential economic attractiveness of the home refuelling concept.

2/ Rix Industries is marketing a second generation of home compressors at $3300 per unit with a minimum of a 1000-unit purchase. This new model has modified features to eliminate the excess oil blow-by experienced with the earlier model. The new unit should be tested more thoroughly to obtain performance and durability data.

3/ Most compressor manufacturers claim the inherent safe operation of their compressors, with a list of comprehensive safety features such as an emergency stop switch, pressure relief valve, inlet and outlet check valves, or encapsulated electric motor. Currently, the most extensively tested compressor is the Rix unit, with a maximum of only 300 test hours. These compressors should be tested more thoroughly to establish a data base for safety acceptability, because these high pressure units will most likely be operated by the general public, who often have limited knowledge about the safety precautions required.

4/ Since the home compressor is designed to be installed outside a user's dwelling, quiet operation of the compressors is an important factor for consumer acceptance of the unit. Manufacturers seldom furnish this information, and there is no documentation on the noise level of the home compressor. Thus, the noise levels of small compressors should be monitored to provide a data base for consumer consideration in determining the acceptability of the product.

5/ The utilization of solid adsorption media will reduce the working pressure of small compressors from 17 to 11 MPa. Thus, two-stage compressors could be used for refuelling, and the compressor cost would be reduced, thereby improving the economic attractiveness of the home refuelling concept. Consequently, the costs and performance of these low pressure compressors and adsorption media should be investigated for their application in natural gas vehicles.

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Table 1/ General Information on Three Home Compressors

Supplier	Rix	Bauer	OMC
Price/unit	$6600	$6837	$5625
Warranty	6 months parts & labour	1 year parts & labour	6 months parts & labour
Dealer	N/A	Safety Supply, Canada	N/A
Service	N/A	Contract negotiable	N/A
Capacity	4.16 m^3/h	6.79 to 8.5 m^3/h	5.09 m^3/h
Fill time (22 m^3)	5.29 h	3.24 to 2.59 h	4.32 h
Present user	Consumers' Gas (Toronto)	People Gas Co. (Pittsburgh)	Consumers' Gas (Toronto)
No. of vehicles serviceable	1-2	1-2	1-2

Table 2/ Design Specifications of Three Home Compressors

Manufacturer	Rix	Bauer	OMC
Output capacity	4.08 m^3/h	6.79-8.50 m^3/h	5.1 m^3/h
Inlet pressure	103 kPa	105-135 kPa	~120 kPa
Outlet pressure	15.51 or 20.68 MPa	Max. 34.47 MPa	Max. 24.82 MPa
Cabinet	encapsulated	sound insulated removable top for easy service	sound insulated removable top for easy service
Size	1.44 x 0.72 m		0.46 x 0.68 x 1.09 m
Weight	N/A	N/A	136 kg
Compressor head			
No. of cylinders	3	3	3
No. of stages	3	3	3
Compession ratio/working pressure			
1st stage	6.5	N/A	0.62 MPa
2nd stage	4.1	N/A	4.65 MPa
3rd stage	5.6	N/A	24.82 MPa
Stroke	23.87 mm	40 mm	24 mm
Sump and reservoir capacity	N/A	2.84 L	1.113 L
Speed	1750 rpm	1200 rpm	2350 rpm
Electric drive motor			
Power rating	1.5 kW	2.24 kW	2.24 kW
Speed	1750 rpm	3450 rpm	3450 rpm
Phase	Single	-	single
Voltage required	230 V	230 V	230 V
Cycles	60 Hz	60 Hz	60 Hz
Gas components			auto gas shut-off valve
Filter			
Low pressure	N/A	N/A	30 μ
Dual high pressure			coalescing dual element
Rating			99.99% retention of 0.6 μ particles
Check valves			
Inlet	N/A	N/A	disc type
Discharge	N/A	N/A	ball type
Electrical safety control components		N/A	high-low pressure switch high temperature switch
Electrical components (Explosion-proof)	external, safe pak		boxes, safe pak

Table 3/ Standard Equipment List Rix "Home-Gas" Compressor, Model HG-3

Rix Three-Stage Lubricated SA-3G Natural Gas Compressor

1/ Wobble-plate drive assembly
2/ Oil-flooded ball bearings
3/ Replaceable cylinder liners
4/ Stainless steel reed valves, all stages
5/ Intercoolers and aftercooler
6/ Aluminum compressor block
7/ TFE piston rings
8/ Free-floating third stage piston
9/ Interstate and discharge relief valves
10/ Internal inlet gas piping
11/ Electric terminal box, NEMA 4
12/ Capsule pressure regulating system
13/ 2 HP, 1750 rpm direct-drive motor -- 220 V/60 Hz/10 with special oil and natural gas compatible insulation, external capacitor start and switching
14/ Flexible coupling for compressor drive
15/ Lubricating and coolant oil pump with direct-drive coupling
16/ External fin-tube type coolant radiator with fan and shroud
17/ External pressure switch, NEMA 4
18/ Discharge temperature switch, NEMA 4
19/ Discharge back pressure valve
20/ Gas-tight bulkhead electrical fittings
21/ Compressor unit and motor support bracket
22/ Compressor unit mounting flange, blind, ASA specs
23/ 10" I.D. ASTM A-53 steel pipe capsule with slip-on flange
24/ Carbon steel main drive shaft
25/ Compressor unit capsule mounting legs
26/ Tamper proof control enclosure

Table 4/ Equipment List of Bauer-Dominus Compressor

1/ Gas-tight inlet filter
2/ Air-cooled intercoolers
3/ Air-cooled aftercooler
4/ Relief valve for each stage
5/ Automatic condensate drain system
6/ Final pressure gauge
7/ Final pressure switch
8/ Air-blast cooling fan
9/ Final oil/moisture separator

Table 5/ Operational Problems of the Rix Compressor as Reported by the Consumers' Gas Company

Problems Encountered	Faulty Relief Valve (3rd Stage)	Oil Blow-by	Fractured Piston and Valve Stem (2nd Stage)
Number of Occurrences	1	24 mL/h of operation	1
Result	gas recirculation within the capsule	oil accumulated in vehicle regulator and gas storage tanks	low flow low pressure
Corrective Action	replaced valve	installed a splash plate in the number one piston	installed new piston and cylinder

Table 6/ Operational Problems of the Rix Compressor as Reported by Canadian Gas Institute

Problems Encountered	Cooling Tube Fracture	Discharge Valve Fracture (2nd or 3rd Stage)	Protection Heater Overload	Faulty Pressure Relief Valve (3rd Stage)	Detonation	Oil Blow-by
Number of Occurrences	2	4	3	2	1	51 mL/h
Result	pressure buildup in capsule	low interstage pressure	compressor stopped	gas was recirculated within capsule	valve perimeter bent	oil accumulated in storage tank
Corrective Action	tube replaced	valves replaced	replaced with #B22 heater rated at 13.7-14.6 A	replaced	replaced	splash guard installed

Table 7/ Estimation of Theoretical Compressor Power Requirement of the Rix Unit by Enthalpy-Entropy Diagram

	STAGE 1		STAGE 2		STAGE 3	
	Suction	Discharge	Suction	Discharge	Suction	Discharge
Pressure (MPa)	0.1518	0.9867	0.9522	3.92	3.802	21.34
% Heat Removal		30		27		30
Temperature (°C)	15.6	146	106.7	243.4	206	371
Compression Ratio	6.5		4.1		5.6	
Power Requirement (kW)						

Total Power = 0.8016 kW

Table 8/ Estimation of Theoretical Compressor Power Requirement of the Rix Unit by Isentropic Formula

	STAGE 1		STAGE 2		STAGE 3	
	Suction	Discharge	Suction	Discharge	Suction	Discharge
Temperature (°C)	15.6	175.6	127.6	285	242.4	500.6
Reduced Temperature	1.5	2.33	1.75	2.45	2.00	2.97
Pressure (MPa)	0.1518	0.9867	0.9570	3.924	3.8060	21.96
Reduced Pressure	0.0328	0.2134	0.2070	0.8488	0.8233	4.75
Compressibility Factor Z	0.9975	0.9960	0.9975	1.0030	0.9980	1.055
Mean Compressibility Zm	0.9967		1.0003		1.027	
Power (kW)	0.2465		0.2446		0.4105	

Total Power = 0.9016 kW

Table 9/ Economic Feasibility Parameters for Vehicle Conversion to CNG Refuelling [12]

General
- current gasoline price
- current natural gas price
- number of vehicles

Vehicle Specific Data
- average kilometres travelled per year
- average fuel consumption
- fuel economy change after conversion to natural gas
- conversion equipment and installation cost
- anticipated changes in vehicle maintenance costs per year
- average vehicle life

Refuelling Station Costs
- compressor cost
- site preparation required (grading, curbing, spreading gravel, etc.)
- compressor maintenance
- compressor power (electricity) requirements
- cascade size (quick-fill only)
- extension of utility lines

Taxes
- federal income
- provincial income
- investment tax credit

Financial
- debt as percentage of total investment
- interest rate on debt
- short-term interest rate
- currency inflation rate

Price Projections (in constant dollars)
- gasoline price
- natural gas price
- electricity cost
- maintenance cost evaluation

Table 10/ Input Data for Fleet #1 Using Slow-Fill System

Gasoline price, $/L	0.47
Alternative fuel cost, $/L gasoline equivalent	0.24
Average annual km/vehicle	18 000
Average gasoline fuel economy, L/100 km	12.0
Fuel economy gain of natural gas vehicle, %	0
Number of vehicles	2
Increase in maintenance cost, $/year/vehicle	0
Compressor maintenance cost, $/m^3	0.04
Electricity cost, ¢/kWh	5.44
Compressor energy requirement, kWh/m^3	0.466
Tax credit for a new vehicle converted to natural gas, $/vehicle	1580
Conversion equipment cost, $/vehicle	1380
Equipment installation cost, $/vehicle	200
Refuelling facility fixed cost, $	0
Compressor fixed cost, $/unit	6600
Interest rate on long-term debt, %	13.75
Interest rate on accrued savings, %	8.0
Total debt, % of total investment	50.00
Gasoline price projection rate, %	3
Alternative fuel price projection rate, %	2
Electricity price projection rate, %	0
Federal and provincial income tax rate, %	50.0
Currency inflation rate, %	5.0

Table 11/ Economic Analysis of Fleet #1 [15]
(Capital Cost = $6600)

	Years of Operation									
Profit and Loss ($)	1	2	3	4	5	6	7	8	9	10
(A) Investment	6600									
Fuel Savings	994	1034	1075	1118	1163	1209	1257	1306	1357	1410
Depreciation	--	--	--	--	--	--	--	--	--	--
Maintenance Cost	166	174	183	192	201	212	222	234	245	257
Operating Cost	106	111	116	122	128	134	142	147	155	163
Total Cost	272	285	299	314	330	345	364	387	400	420
Actual Savings	722	800	777	804	833	863	893	924	957	989
Interest on Debt Capital	454	408	363	318	272	227	182	136	91	45
Gross Savings	268	340	414	487	561	636	712	788	866	944
Taxes	--	--	--	--	--	--	--	--	--	--
Net Savings	268	340	414	487	561	636	712	788	866	944
Debt Capital Recovery	3300	2970	2640	2310	1980	1650	1320	990	660	330
Debt Capital Payment	330	330	330	330	330	330	330	330	330	330
Cash Flow	-61	10	84	157	231	306	382	459	536	614
PV Cash Flow	-54	6	55	95	125	149	167	180	189	194
Interest on Total Cash Flow	--	--	--	3	15	34	60	93	133	182
Tax on Interest	--	--	--	1	7	17	30	46	67	91
Total Cash Flow	-61	-51	81	158	239	323	412	505	603	705
(B) Total PV Cash Flow	-54	-47	8	103	228	337	544	724	914	1108
Analysis										
Cost/Benefit (A/B)	N/A	N/A	821	64.4	29	17.5	12.1	9.1	7.2	5.96
Average Annual Saving ($)	110.8									
Return on Equity (%)	N/A									
Return on Asset (%)	N/A									

Table 12/ Economic Analysis of Fleet #3
(Capital Cost = $3300)

	Years of Operation									
Profit and Loss ($)	1	2	3	4	5	6	7	8	9	10
(A) Investment	3300									
Fuel Savings	994	1034	1075	1118	1163	1209	1257	1306	1357	1410
Depreciation	--	--	--	--	--	--	--	--	--	--
Maintenance Cost	166	174	183	192	202	212	223	233	245	257
Operating Cost	106	111	116	122	128	134	141	148	155	163
Total Cost	272	285	299	314	329	346	363	381	400	420
Actual Savings	722	749	777	805	834	863	894	925	957	990
Interest on Debt Capital	220	198	176	154	132	110	88	66	44	22
Gross Savings	330	406	490	582	684	798	923	1062	1217	1388
Taxes (0.5)	--	--	--	--	--	--	--	--	--	--
Net Savings	330	406	490	582	684	798	923	1062	1217	1388
Debt Capital Recovery	1650	1485	1320	1150	990	825	660	495	330	165
Debt Capital Payment	165	165	165	165	165	165	165	165	165	165
Cash Flow	330	419	520	633	760	904	1066	1248	1452	1682
PV Cash Flow	290	325	353	378	399	417	432	445	455	463
Interest on Total Cash Flow	--	27	60	101	152	213	285	370	470	586
Tax on Interest	--	13	30	52	76	106	143	185	235	293
Total Cash Flow	330	750	1270	1903	2664	3568	4634	5882	7334	9018
(B) Total PV Cash Flow	290	615	968	1346	1760	2163	2596	3041	3497	3961
Analysis										
Cost/Benefit (A/B)	11.35	5.37	3.41	2.45	1.89	1.53	1.27	1.08	0.94	0.83
Average Annual Saving ($)	396.0									
Return on Equity (%)	24									
Return on Asset (%)	12									

Table 13/ Input Data for Fleet #2 Using Fast and Slow Refuelling

Gasoline price, $/L	0.47
Alternative fuel cost, $/L gasoline equivalent	0.24
Average annual km/vehicle	30 000
Average gasoline fuel economy, L/100 km	15.0
Fuel economy gain of natural gas vehicle, %	0
Number of vehicles	5
Increase in maintenance cost, $/year/vehicle	0
Compressor maintenance cost, $/m^3	0.04
Electricity cost, ¢/kWh	5.44
Compressor energy requirement, kWh/m^3	0.466
Tax credit for a new vehicle converted to natural gas, $/vehicle	1580
Conversion equipment cost, $/vehicle	1380
Equipment installation cost, $/vehicle	200
Refuelling facility fixed cost, $	3400
Compressor fixed cost, $/unit (2 units)	6600
Interest rate on long-term debt, %	13.75
Interest rate on accrued savings, %	8.0
Total debt, % of total investment	50.00
Gasoline price projection rate, %	3
Alternative fuel price projection rate, %	2
Electricity price projection rate, %	0
Federal and provincial income tax rate, %	50.0
Currency inflation rate, %	5.0

Table 14/ Economic Analysis of Fleet #2 Using Fast and Slow Refuelling
(Capital Cost = $16,600)

	Years of Operation									
Profit and Loss ($)	1	2	3	4	5	6	7	8	9	10
(A) Investment	16 600									
Fuel Savings	5 175	5 384	5 600	5 825	6 057	6 297	6 546	6 804	7 070	7 344
Depreciation	1 660	1 660	1 660	1 660	1 660	1 660	1 660	1 660	1 660	1 660
Maintenance Cost	864	907	952	1 000	1 050	1 103	1 158	1 216	1 276	1 340
Operating Cost	548	575	604	634	666	699	734	771	810	850
Total Cost	1 412	1 482	1 556	1 634	1 716	1 802	1 892	1 987	2 086	2 190
Actual Savings	3 763	3 902	4 044	4 191	4 341	4 495	4 652	4 817	4 984	5 144
Interest on Debt Capital	1 141	1 027	913	799	685	571	457	342	228	114
Gross Savings	1 792	2 283	2 797	3 335	3 899	4 489	5 107	5 754	6 432	7 140
Taxable Savings	962	1 452	1 966	2 504	3 068	3 658	4 276	4 924	5 600	6 310
Taxes	481	726	983	1 252	1 534	1 829	2 138	2 462	2 800	3 155
Net Savings	1 311	1 556	1 814	2 083	2 365	2 660	2 967	3 292	3 632	3 985
Debt Capital Recovery	8 300	7 470	6 640	5 810	4 980	4 150	3 320	2 490	1 660	830
Debt Capital Payment	830	830	830	830	830	830	830	830	830	830
Cash Flow	2 971	3 218	3 474	3 743	4 025	4 320	4 629	4 952	5 292	5 645
*PV Cash Flow	2 612	2 486	2 360	2 235	2 113	1 994	1 878	1 767	1 659	1 556
Interest on Total Cash Flow	--	238	495	773	1 072	1 394	1 740	2 110	2 506	2 929
Total Cash Flow	2 971	6 187	9 661	13 404	17 429	21 749	26 378	31 330	36 622	42 267
(B) Total PV Cash Flow	2 612	5 098	7 458	9 693	11 806	13 800	15 678	17 445	19 104	20 661
Analysis										
Cost/Benefit (A/B)	6.36	3.26	2.23	1.71	1.41	1.20	1.06	0.95	0.87	0.80
Average Annual Saving on Cash Flow ($)	2066									
Return on Equity (%)	24									
Return on Asset (%)	12									

*PV -- Present Value

Table 15/ Economic Analysis of Fleet #4 Using Fast and Slow Refuelling
(Capital Cost = $10,000)

Profit and Loss ($)	Years of Operation									
	1	2	3	4	5	6	7	8	9	10
(A) Investment	10 000									
Fuel Savings	5 175	5 384	5 600	5 825	6 057	6 297	6 546	6 803	7 069	7 344
Depreciation	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000	1 000
Maintenance Cost	864	907	952	1 000	1 050	1 103	1 158	1 216	1 276	1 340
Operating Cost	548	575	604	634	666	699	734	771	810	850
Total Cost	1 412	1 482	1 556	1 634	1 716	1 802	1 892	1 987	2 086	2 196
Actual Savings	3 763	3 902	4 044	4 191	4 341	4 495	4 654	4 817	4 984	5 155
Interest on Debt Capital	688	619	550	481	413	344	275	206	138	69
Gross Savings	2 576	2 986	3 417	3 869	4 343	4 839	5 360	5 906	6 478	7 076
Taxable Savings	1 076	2 486	2 914	3 369	3 843	4 339	4 860	5 406	5 978	6 576
Taxes	1 038	1 243	1 458	1 684	1 922	2 170	2 430	2 903	2 989	3 288
Net Savings	1 538	1 743	1 959	2 185	2 421	2 669	2 930	3 203	3 489	3 788
Debt Capital Recovery	5 000	4 500	4 000	3 500	3 000	2 500	2 000	1 500	1 000	500
Debt Capital Payment	500	500	500	500	500	500	500	500	500	500
Cash Flow	2 538	2 743	2 958	3 185	3 421	3 669	3 930	4 203	4 489	4 788
PV Cash Flow	2 231	2 120	2 010	1 902	1 797	1 694	1 595	1 499	1 408	1 300
Int. on Total Cash Flow	-	203	422.5	659	914	1 188	1 481	1 796	2 132	2 491
Total Cash Flow	2 538	5 281	8 361	11 424	14 846	18 515	22 446	26 649	31 138	35 926
Total PV Cash Flow	2 231	4 351	6 239	8 264	10 060	11 754	13 349	14 848	16 256	17 577
Analysis										
Cost/Benefit (A/B)	4.48	2.30	1.57	1.21	0.99	0.85	0.67	0.67	0.62	0.57
Average Annual Saving on Cash Flow ($)	1757									
Return on Equity (%)	34									
Return on Asset (%)	17									

Table 16/ Molar Heat Capacity of Natural Gas at Different Temperatures [13]
($MC_p°$ Ideal Gas State, BTU/lb Mol/°R)

Gas	Chemical Formula	Mol Weight	0°F	50°F	60°F	100°F	150°F	200°F	250°F	300°F
Methane	CH_4	16.042	8.233	8.414	8.456	8.651	8.947	9.277	9.638	10.01
Ethane	C_2H_6	30.068	11.44	12.17	12.32	12.95	13.77	14.63	15.49	16.34
Propane	C_3H_8	44.094	15.64	16.88	17.13	18.17	19.52	20.89	22.25	23.56
N-Butane	C_4H_{10}	58.120	20.80	22.38	22.71	24.07	25.81	27.54	29.23	30.90
Nitrogen	N_2	28.016	6.951	6.954	6.954	6.956	6.963	6.970	6.984	6.998
Carbon Dioxide	CO_2	44.010	8.380	8.698	8.762	9.004	9.282	9.559	10.31	10.05

Table 17/ Calculation of Specific Heat Ratio, k

Natural Gas		Determination of Equivalent Mol Weight		Determination of $MC_p°$ Molar Heat Capacity		Determination of Pseudo Critical Pressure PP_c and Temperature TT_c			
Component Name	Mole Fraction (Y)	Individual Component Mol Weight (M)	(Y x M)	Individual Component $MC_p°$ @ 60°F	Y + $MC_p°$ @ 60°F	Component Critical Pressure P_c psia	Y x P_c	Component Critical Temperature T_c °R	Y x T_c
Methane	0.9550	16.042	15.320	8.456	8.075	673	642.7	344	328.5
Ethane	0.0200	30.068	0.601	12.32	0.246	710	14.2	550	11.0
Propane	0.0010	44.094	0.044	17.13	0.017	617	0.617	666	0.666
Butane	0.0001	58.120	0.006	22.71	0.002	22.71	0.002	766	0.077
Nitrogen	0.0180	28.016	0.504	6.954	0.125	492.45	8.864	227.4	4.093
Carbon Dioxide	0.0034	44.010	0.150	8.762	0.030	1071.63	3.644	547	1.86
Total	1.000	M.W. Mix = 16.625		$MC_p°$ Mix = 8.495		P_c Mix = 670.0		T_c Mix = 346.2°R	

$$K = MC_p/MC_p - 1.986 = 1.31$$

For values of $MC_p°$ at other than 60°F, refer to Table 16.

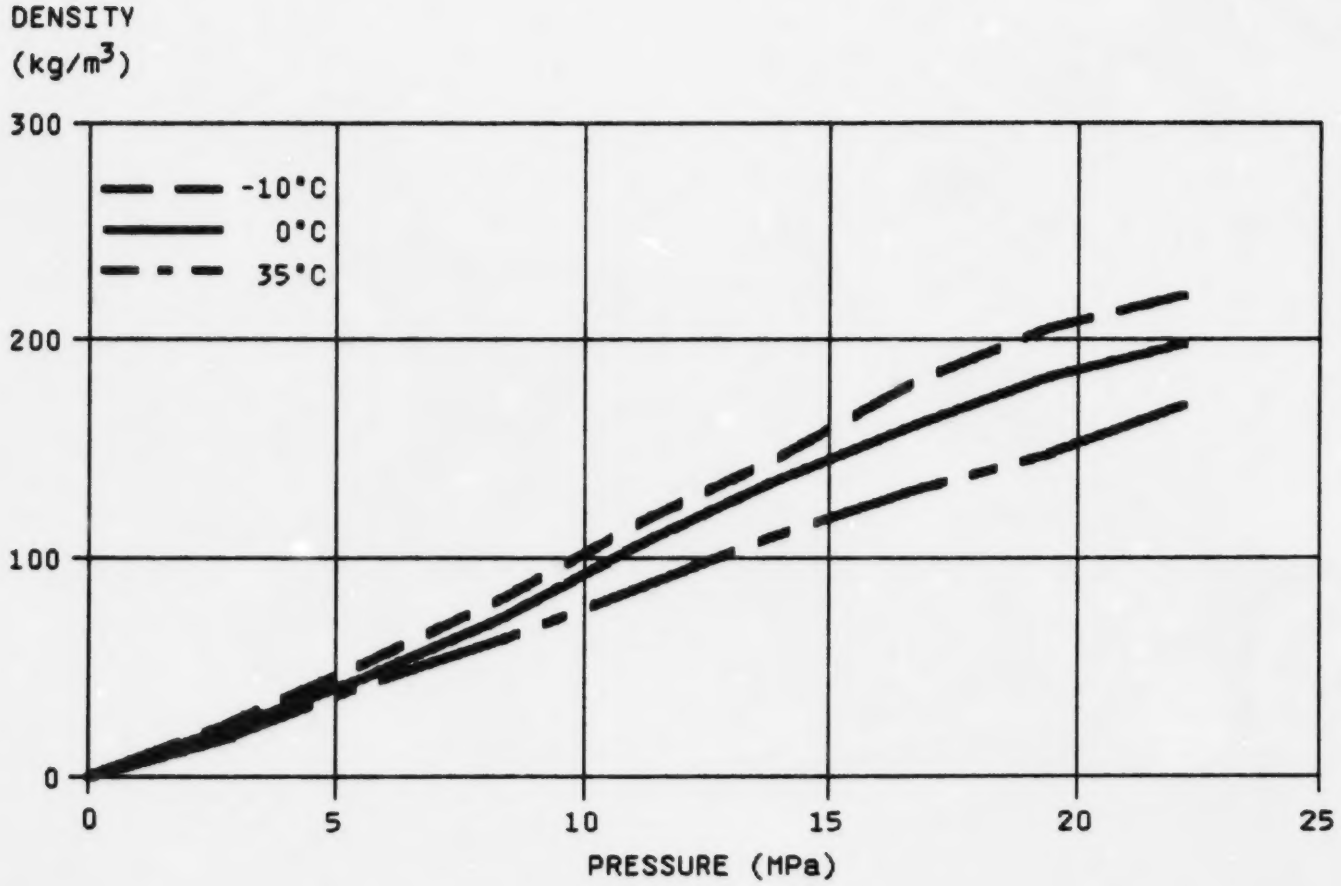


Figure 1/ Density of Natural Gas vs. Storage Pressure

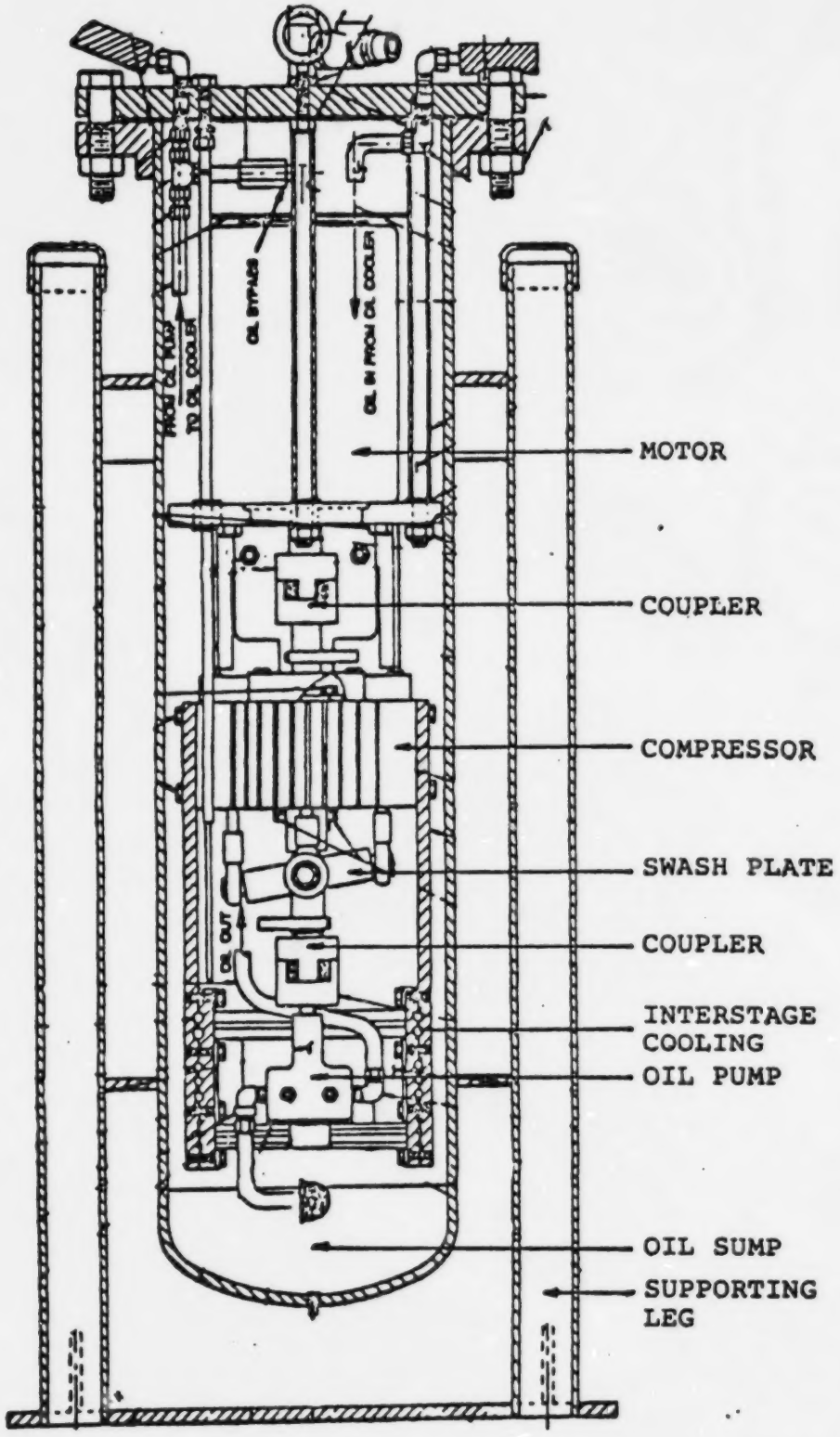


Figure 2/ RIX Compressor General Arrangement

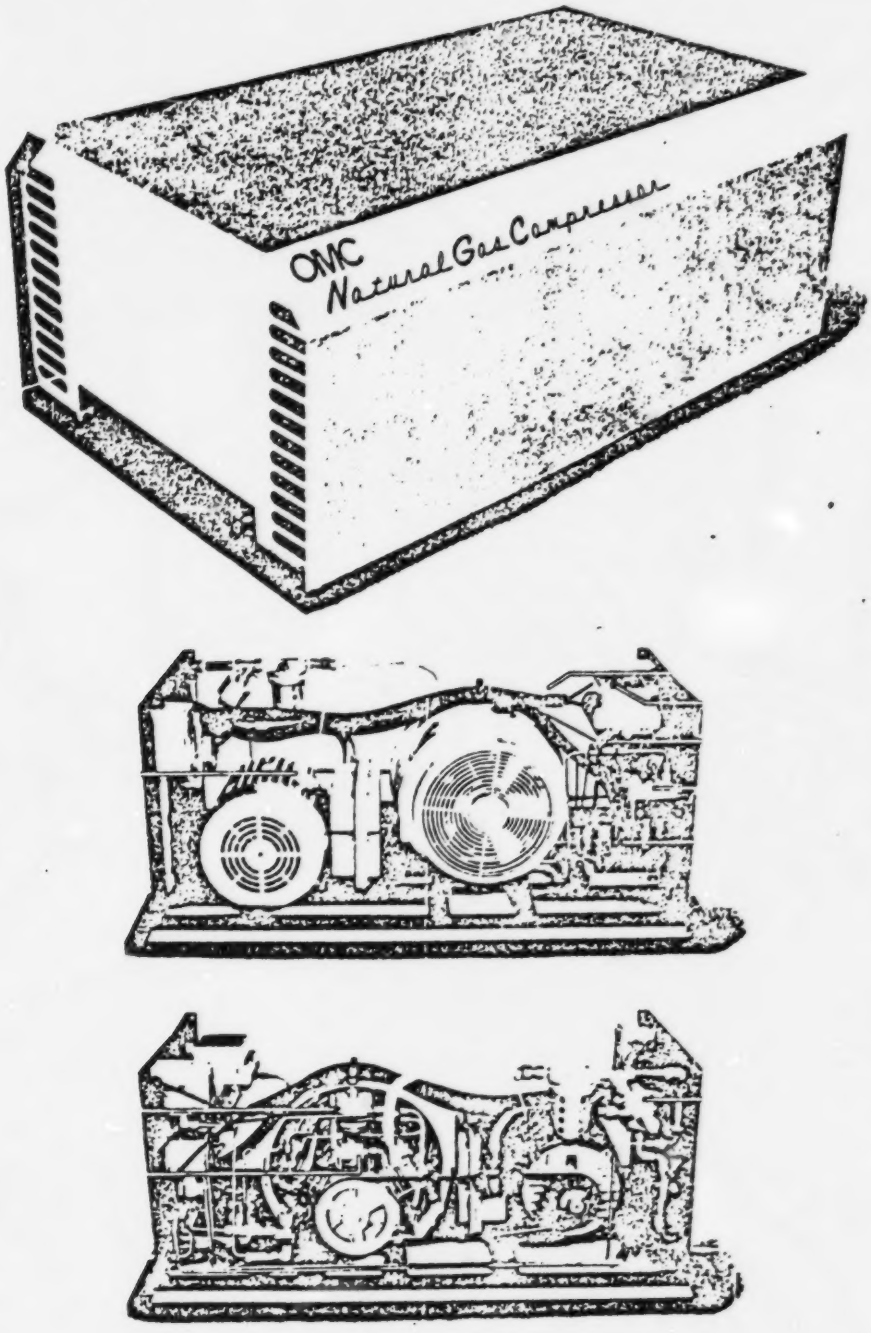


Figure 3/ OMC Compressor

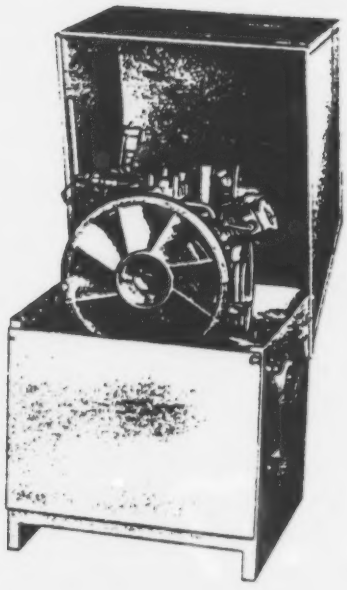
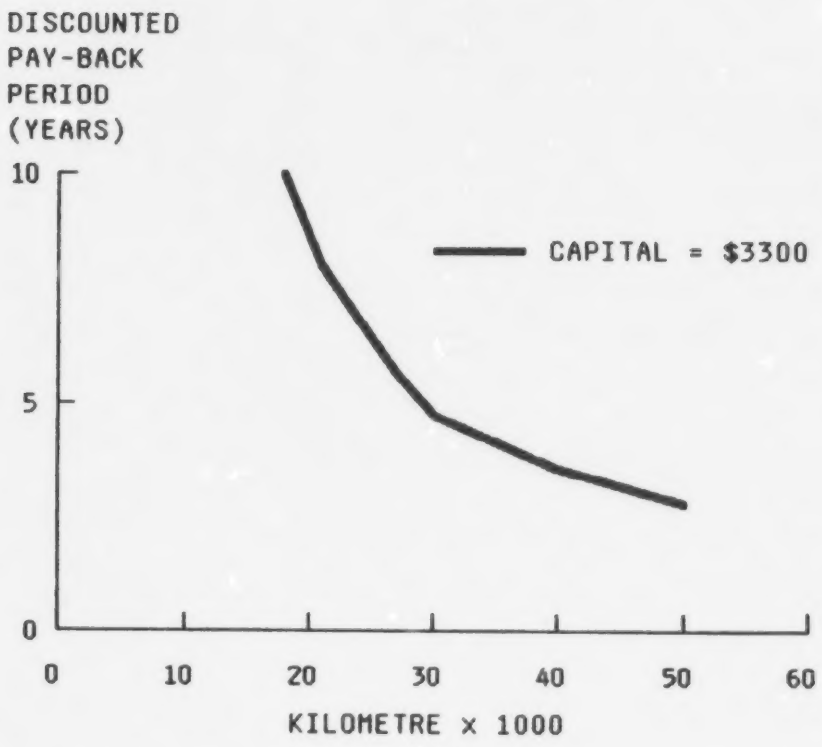


Figure 4/ Bauer Compressor



Distance Travelled by
Each Vehicle Per Year (2 Vehicles/Family)

Figure 5/ Discounted Pay-Back Period for the Application of a Small Compressor in Family Operation

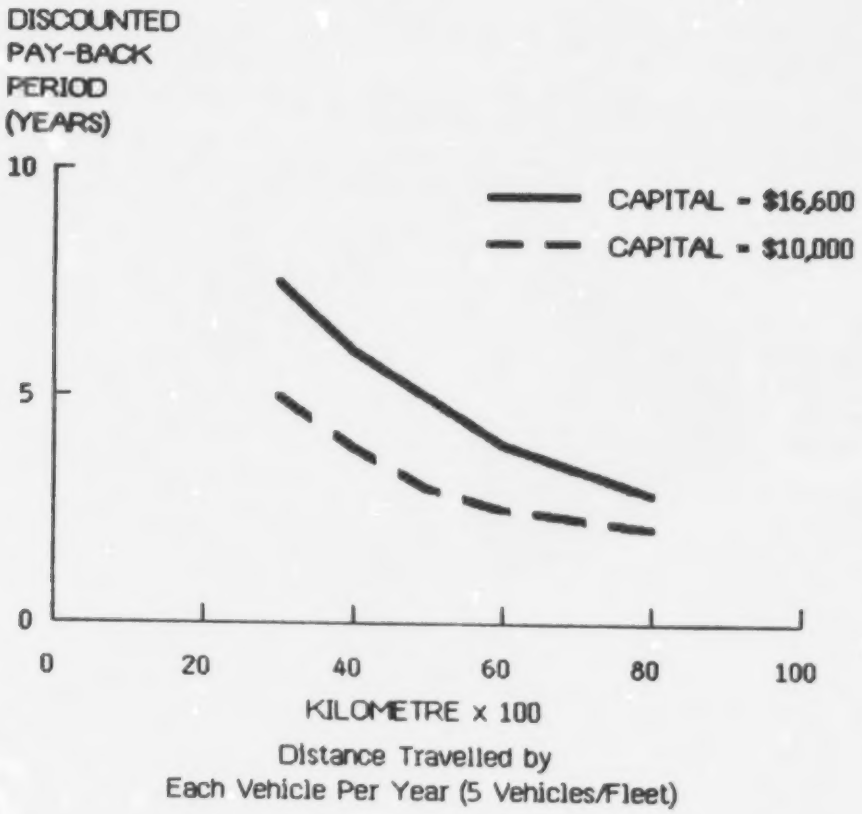


Figure 6/ Discounted Pay-Back Period for the Application of a Small Compressor in Fleet Operation

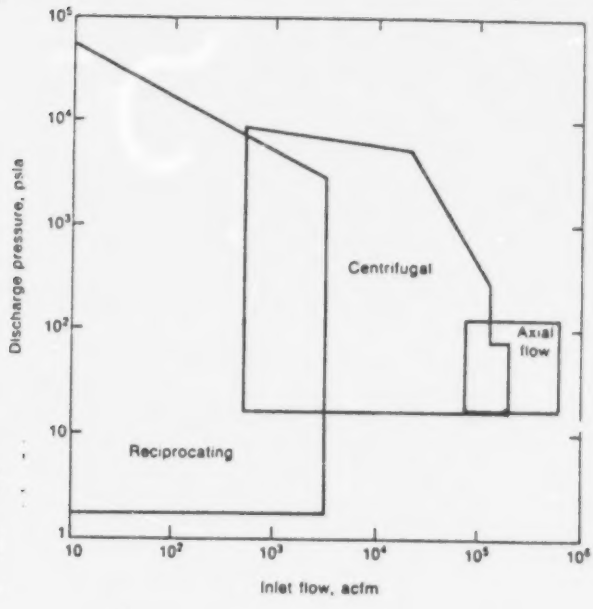


Figure 7/ Approximate Ranges of Application for Reciprocating, Centrifugal, and Axial-Flow Compressors [14]

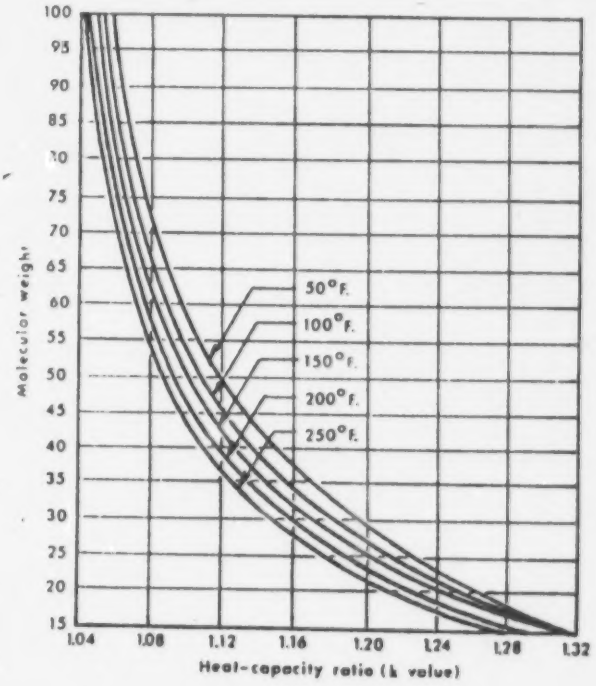


Figure 8/ Approximate Heat-Capacity Ratios of Hydrocarbon Gases [14]

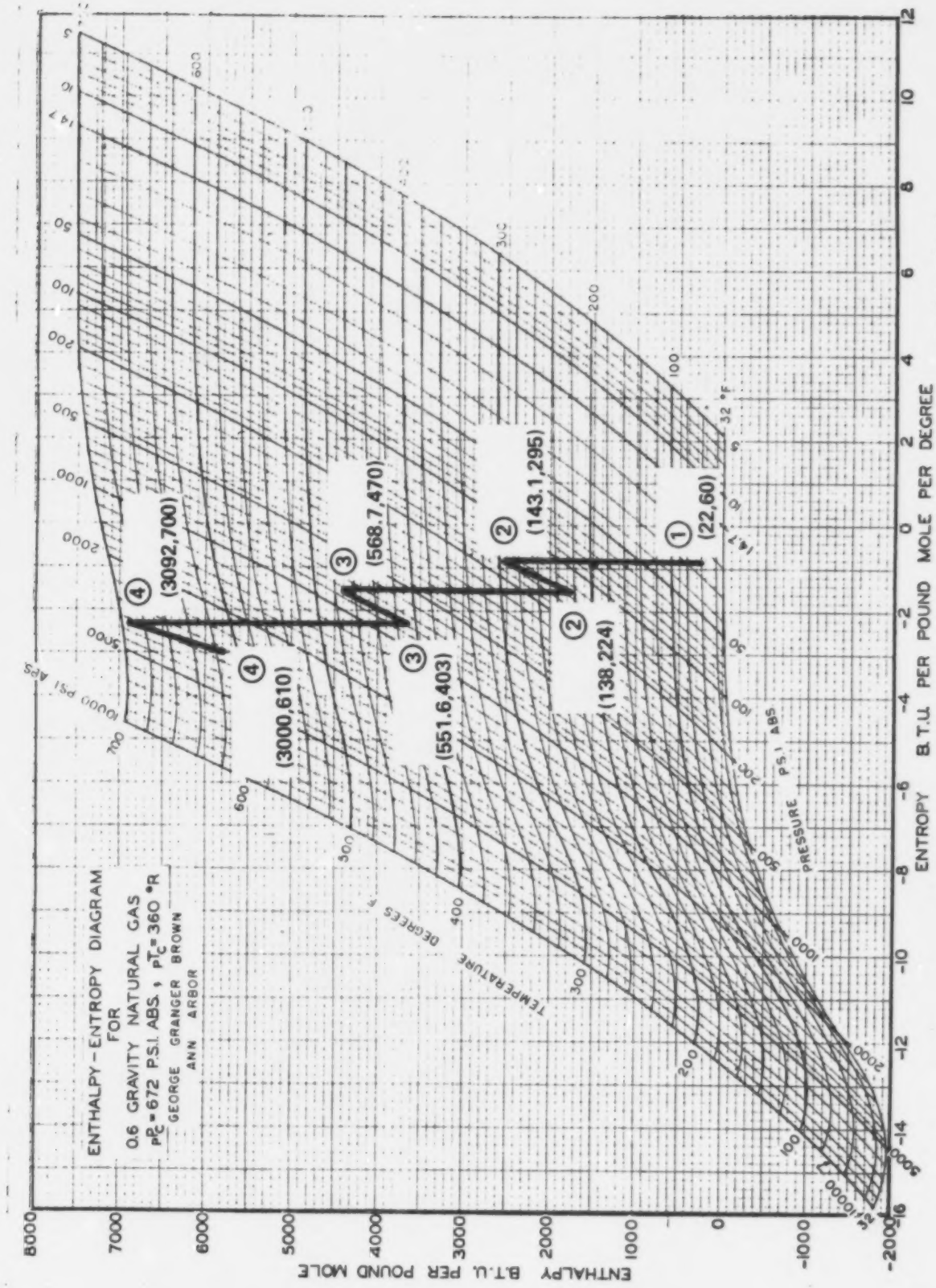


Figure 9/ Enthalpy-Entropy Diagram for 0.6 Gravity Natural Gas (Brown, 4-16. Courtesy AIME.)

APPENDIX A/ THE DENSITY OF NATURAL GAS

Table A.1/ The Density of Natural Gas

(Temperature = 0°C, T_r = 1.45)

Pressure				Compressibility	Density
PSIG	ATM	MPa	P_r	Z	kg/m^3
400	28.21	2.8	0.62	0.91	20.40
800	55.42	5.6	1.22	0.82	44.5
1200	82.63	8.4	1.81	0.74	73.5
1600	109.8	11.2	2.41	0.68	106.2
2000	137.1	13.9	3.01	0.66	136.6
2400	164.3	16.7	3.60	0.67	161.3
2800	191.5	19.4	4.20	0.67	183
3200	218.7	22.2	4.80	0.72	199.8

Table A.2/ The Density of Natural Gas
(Temperature = 35°C, T_r = 1.60)

Pressure				Compressibility	Density
PSIG	ATM	MPa	P_r	Z	kg/m³
400	28.21	2.8	0.62	0.95	19.93
800	55.42	5.6	1.22	0.90	40.51
1200	82.63	8.4	1.81	0.87	62.48
1600	109.8	11.2	2.41	0.84	85.98
2000	137.1	13.9	3.01	0.82	109.9
2400	164.3	16.7	3.60	0.816	132.5
2800	191.5	19.4	4.20	0.822	153.6
3200	218.7	22.2	4.80	0.838	171.3

Table A.3/ The Density of Natural Gas
(Temperature -10°C, T_r = 1.37)

Pressure				Compressibility	Density
PSIG	ATM	MPa	P_r	Z	kg/m³
400	28.21	2.8	0.62	0.91	23.91
800	55.42	5.6	1.22	0.83	51.44
1200	82.63	8.4	1.81	0.77	82.67
1600	109.84	11.2	2.41	0.73	115.9
2000	137.1	13.9	3.01	0.70	150.9
2400	164.3	16.7	3.60	0.70	180.8
2800	191.5	19.4	4.20	0.71	207.8
3200	218.7	22.2	4.80	0.74	227.7

APPENDIX B/ COMPRESSOR PERFORMANCE

This is a technical supplement to the report. The primary objective is to discuss the evaluation of compressor performance, i.e., determining the power requirement and the efficiency. In addition, the effects of temperature rise, compression ratio, and compressibility factor on the compressor power requirement are presented. Also, based on the design specification of the Rix compressor, a sample stage-by-stage calculation of the theoretical power requirement is illustrated by using both an enthalpy-entropy diagram and explicit mathematical expressions.

The main design criteria for a home compressor are to compress the natural gas from 0.137 MPa (20 psia) to 20.7 MPa (3000 psia) with a volumetric flow rate of 4.5 m^3/h (3 scfm). There are three types of compressors: centrifugal, axial, and reciprocating compressors. Figure 7 shows the approximate range of application for the three different types. The major performance characteristics for centrifugal and axial compressors are high volumetric flow and low discharge pressure, which are not applicable to the above design criteria. The reciprocating compressor is characterized by low volumetric flow and high discharge pressure, which meet the design criteria of home compressors. In fact, all currently available home compressors are reciprocating units.

Before discussing the two methods to estimate reciprocating compressor performance, viz, the use of enthalpy-entropy diagrams and explicit thermodynamic relations, a number of necessary terms are defined and discussed in the following.

B.1/ Compression Cycle

The ideal compression cycle is generally assumed to follow an adiabatic reversible (isentropic) path. The compression of an ideal gas follows the equation

$$Pv^k = \text{constant} \qquad (1)$$

where P = absolute pressure
v = molar volume

$k = C_p/C_v$, specific heat ratio

For ideal gases, the value of k can be calculated by knowing the molar heat capacity (MC_p):

$$k = \frac{M \times C_p}{M \times C_p - 1.99} \qquad (2)$$

where M = molecular weight of gas

C_p = heat capacity of the gas at constant pressure, Btu/lb°F

C_v = heat capacity of the gas at constant volume, Btu/lb°F

(Note: Since most of the equations are based on imperial units, only the final results are converted to SI units.)

The heat capacity varies considerably with temperature. Since the temperature of the gas increases as it passes from suction to discharge in the compressor, the value of k is normally determined at the average of suction and discharge temperatures. Table 16 gives values of the heat capacity of natural gas at different temperatures. For a mixture of gases, such as natural gas, the weighted value of molar heat capacity must be determined. A sample calculation for this determination is illustrated in Table 17.

When the gas analysis is not known, the value of molar heat capacity cannot be calculated. However, if the specific gravity of the gas and its operating temperature are known, an approximate value for k can be determined from the molecular weight of the gas, as shown in Figure 8.

B.2/ Compressor Horsepower

Most industrial-scale compressors approach adiabatic operation. The adiabatic formulae, corrected for efficiency, are widely used for reciprocating compressors.

The theoretical horsepower requirement is given by

$$IHP = \frac{0.0642\ Q}{m}\left[\left\{\frac{P_d}{P_s}\right\}^m - 1\right]\frac{T_s}{520}(Z_m) \qquad (3)$$

where Q = volumetric flow rate in standard cubic feet of gas per minute (60°F, 14.7 psia)

$$m = \frac{k - 1}{k}$$

$$k = \frac{C_p}{C_v} = \frac{C_p}{C_p - 1.987}$$ (molar specific heat ratio, using Btu/lb mol °F as units of C_p and C_v)

P_s, P_d = absolute pressure at suction and discharge, respectively, psia

T_s = absolute temperature at suction, °R

$Z = \frac{Z_s + Z_d}{2}$ = mean compressibility factor

Z_s, Z_d = gas law compressibility factor at suction and discharge, respectively

Although this equation is based on an ideal gas with constant specific heat, it gives fairly accurate results for real gases, unless the gas law deviation is large.

For multi-stage compressors, Equation 3 must be applied to each stage to estimate the total horsepower requirement of the complete operation.

B.3/ Multi-Stage Compression Ratio

For a given compression duty, the power requirement is reduced when two or more stages are provided in series, with intercoolers between stages to remove the heat of compression. To estimate the number of stages required to compress a fluid with the same compression ratio in each stage, the following equation can be used:

$$\sqrt[n]{\left(\frac{P°_d}{P°_s}\right)} = \frac{P_d}{P_s} = R_c \qquad (4)$$

where P_d/P_s = the compression ratio for each stage
$P°_d/P°_s$ = the overall compression ratio for multi-stage unit
R_c = the compression ratio for each stage
n = the number of stages

The maximum compression ratio per stage is usually about 3:1 to 4:1. Higher compression ratios can result in reduced volumetric and mechanical efficiencies and greater mechanical stress.

B.4/ Discharge Temperature

The temperature of the gas discharged from the compressor cylinder can be computed from Equation 5:

$$T_d = T_s \left\{\frac{P_d}{P_s}\right\}^m \qquad (5)$$

where T_d = absolute temperature at discharge
T_s = absolute temperature at suction
$m = (h-1)/h$, where h is the molar specific heat ratio

The discharge temperature determined from Equation 5 is the theoretical value and neglects factors such as heat from friction, heat leakage of the intercoolers, and other irreversible effects.

The temperature of the compressed gas is often limited to 250°C, which is close to the flammability limit of most gases. Most unsaturated gases are unstable above 100°C and form heavy gums and smoke.

Multi-stage compressors are often equipped with intercoolers to reduce the temperature of the compressed fluid before subsequent compression. The total amount of energy required for compression is also reduced when the fluid is cooled before the 2nd, 3rd, or 4th stage of compression.

Cooling of the fluid brings the process closer to isothermal conditions, i.e., the ideal case of compression characterized by the minimum work requirement. Hence, the calculation of the power requirement of each compression stage relies on correct estimation of each stage's gas inlet temperature, which is a function of the amount of heat removal of the intercoolers.

B.5/ Calculation of Work Required to Compress Natural Gas by Enthalpy-Entropy Diagram

The compression power requirement of an ideal compression cycle can also be determined using an enthalpy-entropy diagram. The basic energy relationship of any fluid flow process stems from the law of conservation of energy:

$$\Delta H + \text{Kinetic Energy} + \text{Potential Energy} = q - \omega \qquad (6)$$

where $\Delta H = H_2 - H_1$ difference of enthalpy between the initial and final states

q = heat absorbed by system from surroundings

ω = work done by the fluid while in flow

For compression, the kinetic and potential energy due to difference in elevation are neglected, giving

$$\Delta H = q - \omega \qquad (7)$$

In the case of adiabatic compression, the q of Equation 7 is also zero:

$$\therefore \quad -\omega = \Delta H \qquad (8)$$

Equation 8 shows that, at adiabatic or constant entropy conditions for a single stage of compression, the work necessary to compress the gas is equal to the difference in enthalpy between the initial and final stages of compression. For multi-stage compression the ΔH must be calculated separately for each stage and then totalled.

B.6/ Applying the Isentropic Compression Formulae and the Enthalpy-Entropy Diagram

Although isentropic compression is an ideal case, the resulting equations can be applied to real compressors, using appropriate efficiency corrections. The following definitions of efficiency are used in computing the power consumption.

1/ Compression Efficiency, E_c

Compression efficiency accounts for all the power losses that occur between stagnant suction and discharge pressure conditions, including all valve losses.

The compression efficiency is defined as the isentropic horsepower, IHP (from Equation 3), divided by the actual horsepower delivered to the gas, GHP:

$$E_c = \frac{IHP}{GHP} \tag{9}$$

2/ Mechanical Efficiency

Mechanical efficiency, E_m, is the fraction of the drive horsepower (BHP) actually transmitted to the gas for compression. The frictional losses during compression are accounted for by this factor:

$$E_m = \frac{GHP}{BHP} \tag{10}$$

3/ Overall Adiabatic Efficiency

The overall adiabatic efficiency, E_a, is the isentropic horsepower, IHP, divided by the drive brake horsepower, BHP:

$$E_a = \frac{IHP}{BHP} = E_c\, E_m \tag{11}$$

Based on the design specifications of the Rix compressor, the performance parameters of the unit are evaluated by applying Equations 3, 4, 5, and 11. The sample calculation is shown in the following.

Overall Compressor Efficiency Calculations for the Rix Compressor

Stage 1

$T_s = 60°F = 520°R$

$T_r = 520/346.2 = 1.50$

$P_s = 7.3$ psig $= 22.0$ psia

$P_r = 22.0/670 = 0.0328$

$P_d = 6.5 \times 22 = 143$ psia

$P_{dr} = 6.5 \times 0.0328 = 0.2134$

$T_d = 520\ (6.5)^{0.236} = 808.08°R$

$$T_{dr} = \frac{808.08°R}{346.2°R} = 2.33$$

$Z_d = 0.9960$

$Z_s = 0.9975$

$Z_m = 0.9967$

$Q = 2.2$ scfm

$$m = \frac{k - 1}{k} = \frac{0.31}{1.31} = 0.236$$

$$IHP = \frac{0.0642 \times 2.2}{0.236} \left| (6.5)^{0.236} - 1 \right| \frac{520}{520} \times 0.9967$$

$= 0.5985\ (1.554 - 1) \times 0.9967$

$= 0.3305$ HP

Stage 2

Intercooler capacity = 30% Heat Removal Rate

Assume Interstage Pressure Drop = 3%

P_s = 143 x 0.97 = 138.7 psia

P_r = 0.2070

T_s = 808 - (808-520)0.7 = 721.6°R

T_r = 721/346.2 = 2.0826

P_d = 4.1 x 138.7 = 568.7 psia

P_{dr} = 0.8488

T_d = 721 x $(4.1)^{0.236}$ = 1005°R

T_{dr} = 2.91

Z_s = 0.9975

Z_d = 1.003

Z_m = 1.0003

$$IHP_2 = \frac{0.0642 \times 2.2}{0.236} \left|(4.1)^{0.236} - 1\right| \times 1.0003 \times \frac{721}{520}$$

$$= 0.5985 \times 0.3951 \times \frac{721}{520} \times 1.0003$$

= 0.3280 HP

Stage 3

Intercooler Capacity = 27% Heat Removal Rate
Assume Pressure Drop = 3%

P_s = 568.7 x 0.97 = 551.6 psia

P_r = = 0.8233

T_s = 1005 - (1005 - 721) x 0.27 = 928.3

T_{sr} = 928.3/346.2 = 2.68

P_d = 5.6 x 568.7 = 3184 psia

P_{dr} = = 4.75

T_d = 928.3 x $(5.6)^{0.236}$ = 1393°R

T_{dr} = = 4.02

Z_s = = 0.998

Z_d = 1.055

Z_m = 1.027

$$IHP = 0.5985 \times \left[(5.6)^{0.236} - 1\right] \times \frac{928.3}{520} \times 1.027$$

$$= 0.5505 \text{ HP}$$

$$\text{Total IHP} = (0.3305 + 0.3280 + 0.5505) = 1.2090 \text{ HP}$$

$$\text{Overall Efficiency, } E_{ao} = \frac{IHP}{BHP} = \frac{1.2090 \text{ HP}}{2 \text{ HP}} = 0.6045$$

B.7/ Estimation of Compressor Efficiency Using the Enthalpy-Entropy Diagram

The power requirement of an isentropic compression cycle can be readily calculated by using the enthalpy-entropy diagram of the compressed fluid. The isentropic cylce, i.e., the reversible adiabotic cycle, is an ideal cycle which does not involve any irreversible effects such as friction and heat ioss. Thus, it represents the most efficient adiabotic cycle and becomes the reference for efficiency calculations.

To estimate the thermodynamic efficiency of the Rix compressor, the isentropic cycle incorporating its specifications (compression ratios and cooling duties) was drawn on the entropy-enthalpy diagram of natural gas (0.6 gravity) in Figure 9. The initial pressure was selected to be 22.0 psia (7.3 psig), which is representative of the average line pressures experienced in Toronto. At this suction pressure level the isentropic cycle for the Rix compressor results in the discharge condition of 3000 psia and 610°F.

The work involved in the isentropic compression cycle represented in Figure 9 is obtained by the application of the first law of thermodynamics as it applies to a flow system:

$$\Delta H = Q - W$$

The enthalpy change over the cycle is reset from the enthalpy-entropy diagram:

$$\Delta H = H_4' - H_1 = 5700 \text{ Btu/lb mol} - 250 \text{ Btu/lb mol}$$

$$\Delta H = 5450 \text{ Btu/lb mol}$$

The heat exchange with the environment consists of the heat rejected in the interstage and afterstage coolers. The magnitude of this effect can also be estimated from Figure 9:

$$Q = (H_2 - H_2') + (H_3 - H_3') + (H_4 - H_4')$$
$$= (900 + 800 + 1200) \text{ Btu/lb mol} = 2900 \text{ Btu/lb mol}$$

Thus, the amount of work done for pound mole of natural gas is

$$W = Q - \Delta H = (-2900 - 5450) \text{ Btu/lb mol} = -8350 \text{ Btu/lb mol}$$

The power, i.e., rate at which work is done, is obtained by

$$P = W \times \dot{m}$$

where $\dot{m}$ represents the molar flow rate of natural gas processed by the compressor. For the Rix compressor the volumetric flow rate, $\dot{v}$, is specified to be 2.2 ft^3/min, from which the motor flow rate is deduced:

$$\dot{m} = \dot{v} \times \rho/M = (2.2 \text{ ft}^3/\text{min})(0.045 \text{ lb/ft}^3)/(16.63 \text{ lb/lb mol})$$

$$\dot{m} = 0.0060 \text{ lb mol/min}$$

The magnitude of power, P, is then

$$P = (8350 \text{ Btu/lb mol})(0.0060 \text{ /lb mol/min}) = 50.10 \text{ Btu/min},$$

which in metric units becomes 0.882 kW. Thus, the power expended over the isentropic compression cycle is predicted as 0.882 kW. The power rating of the Rix compressor, on the other hand, is 2 HP or 1.491 kW. Therefore, its efficiency, under the suction conditions considered, is estimated as

$$E = \frac{P \text{ (isentropic)}}{P \text{ (actual)}} \times 100 = \frac{0.882}{1.491} \times 100 = 59\%.$$

B.8/ Estimation of Compression Power Using Enthalpy-Entropy Diagram

The procedure for calculating horsepower from an enthalpy-entropy diagram is shown diagrammatically in Figure 9. Using the design specifications of the Rix compressor, the theoretical power requirement can be estimated. Point 1 is the initial state of the gas as it enters the compressor. Paths 1-2, 2'-3, and 3'-4 show the first, second, and third stages or compression (constant entropy). The compressed gas is cooled in the intercooler at constant pressure (paths 2-2', 3-3', and 4-4'). The difference in enthalpy along these paths is equal to the heat removed in the intercoolers. The temperatures at points 2, 3, and 4 are the temperatures of the gas at the end of each compression stage. The temperatures at points 2', 3', and 4' are the temperatures to which the gas is cooled by the intercoolers. The amounts of enthalpy involved in each compression and cooling stage are the following:

$$\text{Total } H = 5250 - 250 = 5000 \text{ Btu/lb mol}$$

$$\Delta H = Q - W \rightarrow -W = \Delta H - Q$$

$$\text{Density of Air} = 1.19 \text{ gm/L} \times \frac{\text{lbm}}{454 \text{ gm}} \times \frac{28.3 \text{ L}}{\text{ft}^3} = 0.0742 \text{ lb/ft}^3$$

$$\text{Density of Natural gas} = \text{Sp. gr.} \times \text{Density of Air} = (0.6)(0.0742)$$
$$= 0.04452 \text{ lb/ft}^3$$

$$\omega = 7550 \frac{\text{Btu}}{\text{lb mol}} \times \frac{1 \text{ lb mol}}{16.625 \text{ lb mol}} \times 0.6 \times 0.0742 \frac{\text{lb}}{\text{ft}^3} \times \frac{2.2 \text{ ft}^3}{\text{min}}$$

$$= 44.48 \text{ Btu/min or}$$

$$= 0.7413 \text{ Btu/s}$$

$$\therefore \text{Compressor Power} = 0.7413 \frac{\text{Btu}}{\text{s}} \times \frac{1.055\,6 \text{ kW}}{\text{Btu/s}} = 0.7825 \text{ kW}$$

and Overall Efficiency, $E_{ao} = \frac{0.7825 \text{ kW}}{2 \text{ HP} \times 0.7457 \frac{\text{kW}}{\text{HP}}} = \frac{0.7825 \text{ kW}}{1.4914 \text{ kW}} = 0.5247$

Notation

$k = C_p/C_v$ = ratio of specific heats

C_p = specific heat at constant pressure

C_v = specific heat at constant volume

M = molecular weight

Z = compressibility factor

P = pressure

T = temperature

IHP = indicate horsepower

Subscripts

c = critical condition

d = discharge of each stage

s = suction of each stage

r = reduced form of temperature and pressure is $\frac{P}{P_c}$ or $\frac{T}{T_c}$

m = mean

1 = first stage

2 = second stage

3 = third stage

APPENDIX C/ SAMPLE ECONOMIC CALCULATIONS AND COMPUTER PROGRAM

C.1/ Fleet #1 (in one year)

Volume of gasoline required per vehicle

$$= \frac{18\ 000}{100} \times 12 = 2160 \text{ L/vehicle/year}$$

Fuel saving for each vehicle (first year)

= gasoline price x gas price index - natural gas price x natural gas price index

= \$0.47 x 1 - \$0.24 x 1

= \$0.23/L gasoline equivalent

Total saving = fuel saving x volume of gas/vehicle x number of vehicles

= \$0.23 x 2160 x 2

= \$993.60

Total cost = (equipment + conversion costs - tax credits) x number of vehicles + compressor costs + facility cost

= \$(1380 + 200 - 1580) x 2 + \$6600 + 0

= \$6600

Volume of natural gas used per vehicle

= volume of gasoline x 0.96 m^3/L

= 2073.6 m^3

Number of hours of compressor operation per vehicle

$$= \frac{2073.6}{4.6\ m^3/h} = 502.24 \text{ h/vehicle}$$

Compressor maintenance cost per vehicle

= \$0.04/m^3 x 2073.6 m^3

= \$82.9/vehicle

Electricity cost per vehicle

= electric cost x compressor energy requirement* x volume of compressed natural gas

= \$0.0544 x 0.466* x 2073

= \$55.25/vehicle

Annual saving = total present value of cash flow/investment life

= \$133.9

C.2/ Fleet #4 (in one year)

Price of gasoline = \$0.47/L

Price of natural gas = \$0.25/m^3 or \$0.242/L gasoline equivalent

Volume of gasoline required per vehicle

$$= 30\ 000\ km \times 15\ \frac{L}{100\ km} = 4500\ L/vehicle/year$$

Fuel saving for each vehicle (first year)

= \$0.47 x 1 - \$0.242 x 1

= \$0.23/L gasoline equivalent

Saving per vehicle

= \$0.23 x 4500

= \$1035/vehicle

Total cost = (equipment + conversion costs - total tax credits) x number of vehicles + compressor costs + facility cost

= \$6600 + \$3400

= \$10,000

---

* NOTE -- Compressor energy requirement is based on results obtained by Consumers' Gas during their testing of the Rix compressor, i.e., 46.6 kWh/m^3.

Volume of natural gas used per vehicle

= 4500 x 0.96 = 4320 m^3

Number of hours of compressor operation per vehicle

$$= 4320\ m^3 \times \frac{h}{4.6\ m^3}$$

= 939.1 h/vehicle

Compressor maintenance cost per vehicle

= \$0.04/m^3 x 4320 m^3

= \$172.80 or \$173/vehicle

Electricity cost per vehicle

= \$0.0544 x 0.466 x 4320

= \$109.5/vehicle

Debt Capital

= investment x debt %

= \$10,000 x 0.5

= \$5000

Total Fuel Savings

= cost saved using natural gas (per litre gasoline equivalent) x volume of gasoline used per vehicle x number of vehicles

= \$0.23/L x 4500 L x 5

= \$5175

Depreciation

= investment/project life

= \$10,000/10 year

= \$1000/year

Debt Capital Payment

= debt capital/ter of debt

= \$5000/10 year

= \$500/year

Maintenance Cost

= maintenance cost per vehicle x vehicle number
= $172.8 x 5
= $864

Operating Cost

= electricity cost per vehicle x vehicle number
= $109.6 x 5
= $548

Total Cost

= maintenance cost + operating cost
= $864 + $548
= $1412

Actual Savings

= total fuel savings - total cost
= $5175 - $1412
= $3763

Interest on Debt Capital

= debt capital x interest on debt
= $5000 x 13.75%
= $688

Gross Savings

= actual savings - interest on debt capital - debt capital payment + interest on cash flow
= $(3763 - 688 - 500 + 0)
= $2575

Debt Capital (year end)

= debt capital - debt capital payment
= $5000 - $500
= $4500

Taxes

= (actual savings + interest on cash flow - depreciation - interest on debt capital) x 0.5

= $(3763 + 0 - 1000 - 688) x 0.5

= $1037.5

Net Savings

= gross savings - tax

= $2575 - $1037.5

= $1538

Cash Flow

= net savings + depreciation

= $1538 + $1000

= $2538

Interest on Cash Flow

= cash flow x savings rate

= $2538 x 0.08 = $203.04 (for next year's income)

Present Value of Cash Flow

$$= \text{cash flow} \times \frac{1}{(1 + \text{interest rate on debt})^{\text{year number}}}$$

$$= \$2538 \times \frac{1}{(1 + 0.1375)^1}$$

= $2231

Cost/Benefit

= investment/total present value of cash flow

= $10,000/$2231

= 4.48

C.3/ Calculation of Rate of Return (Based on Investment by Fleet #4)

Total Annual Savings

= total present value of cash flow/investment life

= $17,576/10 = $1757/year

Return on Equity

= total annual savings/equity

= $1757.6/$5000

= 34%

Return on Asset

= total annual savings/investment

= $1757.6/$10,000

= 17.57%

NOTE: Basic pay period occurs when cost/benefit = 1

∴ Pay-back period = 5 years

C.4/ Computer Program

```
      1
      2 C     COMPESSOR ECONOMIC EVUALATION
      3
      4
      5
      6 C     TPVFOW - TOTAL PRESENT VALUE OF CASH FLOW
      7 C     TCFLOW - TOTAL CASH FLOW
      8 C     ICFLOW - INTEREST ON CASH FLOW
      9 C     TAXINT - TAX ON INTEREST
     10 C     NGI    - TOTAL PRICE INDEX OF NATURAL GAS
     11 C     GI     - TOTAL PRICE INDEX OF GASOLINE
     12 C     MCOSPI - YEARLY PRICE INDEX OF MAINTENANCE COST
     13 C     OCOSPI - YEARLY PRICE INDEX OF OPERATIONAL COST
     14 C     FLOW   - A DUMMY VARIABLE FOR THE TOTALING OF TCFLOW
     15 C     COMREQ - COMPRESSOR ENERGY REQUIREMENT  KwHr/m ***3
     16 C     INTD   - INTEREST RATE ON DEBT .
     17 C     INTS   - INTEREST RATE ON SAVINGS
     18 C     DEBT   - AMOUNT OF DEBT, assume 50% OF THE INVESTMENT
     19 C     DEPREC - AMOUNT OF DEPRECATION, YEARLY AVERAGE
     20 C     VOLGAS - VOLUMN OF GAS USED BY EACH VEHICLE PER YEAR
     21 C     CAPREC - CAPITAL RECOVERY
     22 C     VOLNG  - VOLUMN OF NATURAL GAS USED PER VEHICLE
     23 C     FUELCO - GASOLINE FUEL CONSUMPTION OF THE VEHICLE L/100Km
     24 C     GASP   - PRICE OF GASOLINE
     25 C     NGP    - PRICE OF NATURAL GAS
     26 C     GPI    - YEARLY PRICE INDEX OF GASOLINE
     27 C     NGPI   - YEARLY PRICE INDEX OF NATURAL GAS
     28 C     MCOSTI - TOTAL MAINTENANCE COST PRICE INDEX
     29 C     OCOSTI - OPERATIONAL COST PRICE INDEX
     30 C     MCOST  - TOTAL MAINTENANCE COST, $0.04/ m***3
     31 C     ECOST  - ELECTRICITY COST ,$0.0544/1wH
     32 C     USE    - INDICATOR FOR TAX CALUATION
     33 C              '1' FOR CORPORTATION
     34 C              '0' FOR HOME USE
     35 C     INVEST - TOTAL AMOUNT OF INVESTMENT
     36 C              i.e. COMPRESSOR COST + INSTALLATION COST
     37 C     TOTKM  - TOTAL MILEAGE OF EACH VEHICLE Km/YEAR
     38 C     NUMVEH - NUMBER OF VEHICLES IN THE FLEET
     39 C     I      - INDEX OF YEAR COUNTER, I = 10
     40 C
     41 C
     42 C     FSAV   - FUEL SAVING OF EACH VEHICLE WHEN NATURAL GAS IS
     43 C              USED INSTEAD OF GASOLINE
     44 C     TOFSAV - TOTAL AMOUNT OF FUEL SAVING OF THE FLEET EACH YEAR
     45 C     TMCOST - TOTAL MAINTENANCE COST    $/YEAR
     46 C     TOCOST - TOTAL OPERATIONAL COST    $/YEAR
     47 C     TCOST  - TOTAL COST OF OPERATION,  (TMCOST + TOCOST)
     48 C     SAVING - NET SAVING BY THE FLEET OWNER
     49 C              i.e.  ( TOFSAV - TCOST)
     50 C     INDEBT - AMOUNT OF INTEREST ON DEBT
     51 C     GSAV   - GROSS SAVING  i.e.  SAVING - INDEBT
     52 C     TAX    - CORPORATION TAX RATE
     53 C     NSAV   - NET SAVING AFTER TAX
     54 C     CFLOW  - FOR CORPORATION
     55 C              = DEPRECIATION + NET SAVING - CAPITAL RECOVERY
     56 C              FOR NON - TAXABLE ORGANIZATION
     57 C              = NET SAVING - CAPITAL RECOVERY
     58 C     TCFLOW - TOTAL CASH FLOW i.e. = CASH FLOW + INTEREST ON
     59 C                                     CASH FLOW - TAX ON INTEREST
```

```
C
C
C     PVFLOW - PRESENT VALUE OF CASH FLOW
C     CB     - COST BENEFIT RATIO
C              I.E. INVEST/TPVFOW FOR THAT PERIOD

      REAL TPVFOW,TCFLOW,ICFLOW,TAXINT,NGI,GI,MCOSPI,OCOSPI,FLOW

      REAL COMREQ,INTD,INTS,DEBT,DEPREC,CAPREC,VOLGAS,VOLNG

      REAL FUELCO,GASP,NGP,GPI,NGPI,MCOSTI,OCOSTI,MCOST,ECOST
      INTEGER USE,INVEST,TOTKM,NUMVEH,I
      REAL FSAV,TOFSAV,TMCOST,TOCOST,TCOST,SAVING,INDEBT,GSAV,TAX
      REAL NSAV,CFLOW,PVFLOW,CB


      OPEN (5, FILE='FORT.DAT')
      OPEN (6, FILE='CON')

C




C     READ EITHER CORPORATION OR PRIVATE USE.
C     '1' FOR CORPORATION
C     '0' FOR PRIVATE USE

      READ (5,10) USE
10    FORMAT (I2)
      WRITE (6,610) USE
610   FORMAT ( ' USE = ',I2)
      READ (5,15) INVEST,FUELCO,TOTKM,GASP,NGP,GPI,NGPI,NUMVEH
15    FORMAT (I8,F8.2,I8,4(F6.4,2X),I4)
      WRITE (6,615) INVEST,FUELCO,TOTKM,GASP
615   FORMAT ( ' TOTAL INVESTMENT =',I8,/,
     *         ' FUEL CONSUMPTION (L/100 Km) =',F9.2,/,
     *         ' TOTAL KILOMETERAGE OF EACH VEHICLE EACH YEAR =',I8,/,
     *         ' GASOLINE PRICE ( $/L) =',F6.4)
      WRITE (6,616) NGP,GPI,NGPI,NUMVEH
616   FORMAT ( ' NATURAL GAS PRICE ( $/L) =',F6.4,/,
     *         ' GASOLINE PRICE INDEX =',F6.4,/,
     *         ' NATURAL GAS PRICE INDEX =',F6.4,/,
     *         ' TOTAL NUMBER OF VEHICLE =',I4)

      READ (5,20) MCOSPI,OCOSPI,MCOST,ECOST,COMREQ,INTD,INTS
20    FORMAT (7F8.4)
      WRITE (6,620) MCOSPI,OCOSPI,MCOST,ECOST,COMREQ,INTD,INTS
620   FORMAT ( ' MAINTENANCE COST INDEX           =',F8.4,/,
     *         ' OPERATIONAL COST INDEX           =',F8.4,/,
     *         ' MAINTENANCE COST ( $/m***3)      =',F8.4,/,
     *         ' ENERGY COST ( $/Kmh )            =',F8.4,/,
     *         ' COMPRESSOR REQUIREMENT (kMH/Hr) =',F8.4,/,
     *         ' INTEREST RATE ON DEBT, %         =',F8.4,/,
     *         ' INTEREST RATE ON SAVING, %       =',F8.4)
      NGI=1
      GI=1
      MCOSTI=1
```

```
      OCOSTI=1
      TPVFOW=0
      TCFLOW=0
      ICFLOW=0
      TAXINT=0
      FLOW =0
      DEBT=INVEST/2.
      DEPREC=INVEST/10.
      CAPREC=DEBT/10.
      VOLGAS=TOTKM*FUELCO/100.
      VOLNG=VOLGAS*0.96


      DO 999  I=1,10

      FSAV=(GASP*GI)-(NGP*NGI)
      TOFSAV=FSAV*VOLGAS*NUMVEH
      TMCOST=MCOST*VOLNG*NUMVEH*MCOSTI
      TOCOST=ECOST*COMREC*VOLNG*NUMVEH*OCOSTI
      TCOST=TMCOST+TOCOST
      SAVING=TOFSAV-TCOST
      INDEBT=DEBT*INTD
      GSAV=SAVING-INDEBT-CAPREC+ICFLOW


      IF (USE.EQ.0)  GO TO 100
      TAX=(SAVING+ICFLOW-DEPREC-INDEBT)*.5
      NSAV=GSAV-TAX
      CFLOW=DEPREC+NSAV
      GO TO 101
100   TAX=0
      NSAV=GSAV
      CFLOW=NSAV+ICFLOW-TAXINT

101   TCFLOW=CFLOW+TCFLOW
      PVFLOW=CFLOW*1/((1+INTD)**I)
      TPVFOW=TPVFOW+PVFLOW
      CB=INVEST/TPVFOW

      WRITE (6,62) I
62    FORMAT ( 10X,' YEAR =',I2)

      WRITE (6,60) TOFSAV,TMCOST,TOCOST,TCOST,SAVING,INDEBT,GSAV,TAX,
     *             NSAV
60    FORMAT ( ' TOTAL FUEL SAVING =',F8.2,/,
     *         ' TOTAL MAINTENANCE COST=',F8.2,/,
     *         ' TOTAL OPERATION COST =',F8.2,/,
     *         ' TOTAL COST =',F8.2,/,
     *         ' ACTUAL SAVING =  ',F8.2,/,
     *         ' INTEREST ON DEBT =',F8.2,/,
     *         ' GROSS SAVING =',F8.2,/,
     *         ' TAX =    ',F8.2,/,
     *         ' NET SAVING =', F8.2)

      WRITE (6,61) DEBT,CAPREC,CFLOW
61    FORMAT (' DEBT =',F8.2,/,
     *        ' DEBT PAYMENT =',F8.2,/,
     *        ' CASH FLOW =',F8.2)

```

```
1    178        WRITE (6,62) ICFLOW,TAXINT,TCFLOW,PVFLOW,TPVFOW,CB
1    179 62     FORMAT (     ' INTEREST ON CASH FLOW=',F8.2,/,
1    180       *             ' TAX ON INTEREST OF CASH FLOW=',F8.2,/,
1    181       *             ' TOTAL CASH FLOW=',F8.2,/,
1    182       *             ' PRESENT VALUE OF CASH FLOW=',F8.2,/,
1    183       *             ' TOTAL PRESENT VALUE OF CASH FLOW=',F8.2,/,
1    184       *             ' CASH/ BENEFIT =',F8.2)
1    185        ICFLOW=TCFLOW*INTS
1    186        TAXINT=ICFLOW*0.5
1    187        DEBT=DEBT-CAPREC
1    188        MCOSTI=MCOSTI*MCOSPI
1    189        OCOSTI=OCOSTI*OCOSPI
1    190        GI=GI*GPI
1    191        NGI=NGI*NGPI
1    192 999    CONTINUE
     193        STOP
     194        END
```

Name	Type	Offset	P	Class
CAPREC	REAL	1104		
CB	REAL	1168		
CFLOW	REAL	1160		
COMPED	REAL	598		
DEBT	REAL	1096		
DEPREC	REAL	1100		
ECOST	REAL	594		
FLOW	REAL	1092		
FSAV	REAL	1120		
FUELCO	REAL	32		
GASP	REAL	40		
GI	REAL	1064		
GPI	REAL	48		
GSAV	REAL	1148		
I	INTEGER*4	1116		
ICFLOW	REAL	1084		
INDEBT	REAL	1144		
INTD	REAL	602		
INTS	REAL	606		
INVEST	INTEGER*4	28		
MCOSPI	REAL	582		
MCOST	REAL	590		
MCOSTI	REAL	1068		
NGI	REAL	1060		
NGP	REAL	44		
NGPI	REAL	52		
NSAV	REAL	1156		
NUMVEH	INTEGER*4	56		
OCOSPI	REAL	586		
OCOSTI	REAL	1072		
PVFLOW	REAL	1164		
SAVING	REAL	1140		
TAX	REAL	1152		
TAXINT	REAL	1088		
TCFLOW	REAL	1080		
TCOST	REAL	1136		
TMCOST	REAL	1128		
TOCOST	REAL	1132		
TOFSAV	REAL	1124		

```
TOTKM   INTEGER*4        36
TPVFOW  REAL           1076
USE     INTEGER*4         2
VOLGAS  REAL           1108
VOLNG   REAL           1112


Name    Type             Size   Class

MAIN                            PROGRAM

 Pass One     No Errors Detected
              194 Source Lines
```

```
@tfort

USE =  1
TOTAL INVESTMENT =    10000
FUEL CONSUMPTION (L/100 km) =    15.00
TOTAL KILOMETERAGE OF EACH VEHICLE EACH YEAR =    30000
GASOLINE PRICE ( $/L) = .4700
NATURAL GAS PRICE ( $/L) = .2400
GASOLINE PRICE INDEX =1.0300
NATURAL GAS PRICE INDEX =1.0200
TOTAL NUMBER OF VEHICLE =    5
MAINTENANCE COST INDEX              =  1.0500
OPERATIONAL COST INDEX              =  1.0500
MAINTENANCE COST ( $/a***3)         =    .0400
ENERGY COST ( $/Kwh )               =    .0544
COMPRESSOR REQUIREMENT (KW/Hr)      =    .4660
INTEREST RATE ON DEBT, %            =    .1375
INTEREST RATE ON SAVING, %          =    .0800
          YEAR = 1
TOTAL FUEL SAVING = 5175.00
TOTAL MAINTENANCE COST=  864.00
TOTAL OPERATION COST =  647.57
TOTAL COST = 1411.57
ACTUAL SAVING =    3763.43
INTEREST ON DEBT =  687.50
GROSS SAVING = 2575.93
TAX =     1037.97
NET SAVING = 1537.97
DEBT = 5000.00
DEBT PAYMENT =  500.00
CASH FLOW = 2037.97
INTEREST ON CASH FLOW=      .00
TAX ON INTEREST OF CASH FLOW=      .00
TOTAL CASH FLOW= 2537.97
PRESENT VALUE OF CASH FLOW= 2231.18
TOTAL PRESENT VALUE OF CASH FLOW= 2231.18
CASH/ BENEFIT =     4.48
          YEAR = 2
TOTAL FUEL SAVING = 5384.25
TOTAL MAINTENANCE COST=  907.20
TOTAL OPERATION COST =  574.95
TOTAL COST = 1482.15
ACTUAL SAVING =    3902.10
INTEREST ON DEBT =  618.75
GROSS SAVING = 2986.39
TAX =     1243.20
NET SAVING = 1743.20
DEBT = 4500.00
DEBT PAYMENT =  500.00
CASH FLOW = 2743.20
INTEREST ON CASH FLOW=  203.04
TAX ON INTEREST OF CASH FLOW=  101.52
TOTAL CASH FLOW= 5281.16
PRESENT VALUE OF CASH FLOW= 2120.09
TOTAL PRESENT VALUE OF CASH FLOW= 4351.27
CASH/ BENEFIT =     2.30
```

```
          YEAR = 3
TOTAL FUEL SAVING = 5606.36
TOTAL MAINTENANCE COST=  952.5
TOTAL OPERATION COST =  603.69
TOTAL COST = 1556.25
ACTUAL SAVING =  4044.
INTEREST ON DEBT =  550.00
GROSS SAVING = 3417.10
TAX =  1458.55
NET SAVING = 1958.55
DEBT = 4000.00
DEBT PAYMENT =  500.00
CASH FLOW = 1958.55
INTEREST ON CASH FLOW=  133.49
TAX ON INTEREST OF CASH FLOW=  211.25
TOTAL CASH FLOW= 8279.71
PRESENT VALUE OF CASH FLOW= 2010.13
TOTAL PRESENT VALUE OF CASH FLOW=
CASH/ BENEFIT =  1.57
          YEAR = 4
TOTAL FUEL SAVING =
TOTAL MAINTENANCE COST=
TOTAL OPERATION COST =  653.88
TOTAL COST =
ACTUAL SAVING =  4191.00
INTEREST ON DEBT =  491.25
GROSS SAVING = 3960.92
TAX =  1684.46
NET SAVING = 2182.46
DEBT =
DEBT PAYMENT =
CASH FLOW =
INTEREST ON CASH FLOW=  659.13
TAX ON INTEREST OF CASH FLOW=  329.57
TOTAL CASH FLOW=11424.17
PRESENT VALUE OF CASH FLOW=
TOTAL PRESENT VALUE OF CASH FLOW= 2263.49
CASH/ BENEFIT =  1.41
          YEAR =
TOTAL FUEL SAVING =
TOTAL MAINTENANCE COST=
TOTAL OPERATION COST =  685.07
TOTAL COST = 1715.77
ACTUAL SAVING =  4341.25
INTEREST ON DEBT =  412.50
GROSS SAVING = 3342.78
TAX =  1921.39
NET SAVING = 2421.39
DEBT = 3000.00
DEBT PAYMENT =  500.00
CASH FLOW = 3421.39
INTEREST ON CASH FLOW=  913.91
TAX ON INTEREST OF CASH FLOW=  456.97
TOTAL CASH FLOW=14845.56
PRESENT VALUE OF CASH FLOW= 1796.58
TOTAL PRESENT VALUE OF CASH FLOW=
CASH/ BENEFIT =  .99
```

```
          YEAR = 6
TOTAL FUEL SAVING = 6297.29
TOTAL MAINTENANCE COST= 1102.71
TOTAL OPERATION COST =  698.85
TOTAL COST = 1901.56
ACTUAL SAVING =   4495.73
INTEREST ON DEBT =  343.75
GROSS SAVING = 4839.62
TAX =    2169.81
NET SAVING = 2669.81
DEBT = 2500.00
DEBT PAYMENT =  500.00
CASH FLOW = 3665.81
INTEREST ON CASH FLOW= 1187.65
TAX ON INTEREST OF CASH FLOW=  593.82
TOTAL CASH FLOW=18515.37
PRESENT VALUE OF CASH FLOW= 1674.08
TOTAL PRESENT VALUE OF CASH FLOW=11754.15
CASH/ BENEFIT =     .85
          YEAR = 7
TOTAL FUEL SAVING = 6645.82
TOTAL MAINTENANCE COST= 1157.84
TOTAL OPERATION COST =  733.79
TOTAL COST = 1891.64
ACTUAL SAVING =   4754.19
INTEREST ON DEBT =  275.00
GROSS SAVING = 5260.42
TAX =    2430.21
NET SAVING = 2930.21
DEBT = 2000.00
DEBT PAYMENT =  500.00
CASH FLOW = 2930.21
INTEREST ON CASH FLOW= 1465.23
TAX ON INTEREST OF CASH FLOW=  740.61
TOTAL CASH FLOW=22419.58
PRESENT VALUE OF CASH FLOW= 1594.98
TOTAL PRESENT VALUE OF CASH FLOW=13349.13
CASH/ BENEFIT =     .75
          YEAR = 8
TOTAL FUEL SAVING = 6803.01
TOTAL MAINTENANCE COST= 1215.73
TOTAL OPERATION COST =  770.48
TOTAL COST = 1986.22
ACTUAL SAVING =   4816.79
INTEREST ON DEBT =  206.25
GROSS SAVING = 5906.19
TAX =    2703.10
NET SAVING = 3203.10
DEBT = 1500.00
DEBT PAYMENT =  500.00
CASH FLOW = 4203.10
INTEREST ON CASH FLOW= 1795.65
TAX ON INTEREST OF CASH FLOW=  897.82
TOTAL CASH FLOW=26648.68
PRESENT VALUE OF CASH FLOW= 1499.54
TOTAL PRESENT VALUE OF CASH FLOW=14948.67
CASH/ BENEFIT =     .67
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          YEAR = 9
TOTAL FUEL SAVING = 7069.13
TOTAL MAINTENANCE COST= 1276.52
TOTAL OPERATION COST =  809.01
TOTAL COST = 2085.53
ACTUAL SAVING =   4983.60
INTEREST ON DEBT =  137.50
GROSS SAVING = 6478.00
TAX =    2989.00
NET SAVING = 3489.00
DEBT = 1000.00
DEBT PAYMENT =  500.00
CASH FLOW = 4489.00
INTEREST ON CASH FLOW= 2131.89
TAX ON INTEREST OF CASH FLOW= 1065.95
TOTAL CASH FLOW=31137.68
PRESENT VALUE OF CASH FLOW= 1407.95
TOTAL PRESENT VALUE OF CASH FLOW=16256.61
CASH/ BENEFIT =     .62
          YEAR =10
TOTAL FUEL SAVING = 7344.48
TOTAL MAINTENANCE COST= 1340.35
TOTAL OPERATION COST =  849.46
TOTAL COST = 2189.81
ACTUAL SAVING =   5154.67
INTEREST ON DEBT =   68.75
GROSS SAVING = 7076.93
TAX =    3288.47
NET SAVING = 3788.47
DEBT =  500.00
DEBT PAYMENT =  500.00
CASH FLOW = 4788.47
INTEREST ON CASH FLOW= 2491.01
TAX ON INTEREST OF CASH FLOW= 1245.51
TOTAL CASH FLOW=35926.14
PRESENT VALUE OF CASH FLOW= 1320.33
TOTAL PRESENT VALUE OF CASH FLOW=17576.94
CASH/ BENEFIT =     .57
Stop - Program terminated.
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